ZOOPLANKTON STUDIES IN 1977 AND 1978 AT THE DONALD C. COOK NUCLEAR POWER PLANT: COMPARISONS OF PREOPERATIONAL (1971-1974) AND OPERATIONAL (1975-1978) POPULATION CHARACTERISTICS

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SUMMARY

This report contains the results of investigations conducted in 1977 and 1978 which evaluated the impact of the operation of the cooling water system of the Donald C. Cook Nuclear Power Plant on zooplankton populations in southeastern Lake Michigan. Both the immediate effects of condenser passage and the effects of plume entrainment are considered. Unit 1 has been operational since February 1975 and Unit 2 has been operational since April 1978. Both units were inoperative at various times during the study period.

Temperature and Secchi disc depths were measured during 17 monthly surveys (April to December 1977 and April to November 1978). Ambient surface-water temperatures ranged from less than 1°C to 24°C. While water temperatures were similar in the 2 years, some differences did occur, particularly in spring. Surface-water temperatures were a few C° higher in April, May, and June 1977 than in 1978. An upwelling was observed during both June cruises and the July 1978 cruise, while a weak upwelling occurred during the September 1978 cruise.

The thermal plume (-T 0.5C°) was limited to a comparatively small area (<3 km^2) of the survey grid (250 km^2). Condenser-passed water was diluted within minutes to 30% of its original concentration by mixing with lake water. This intense mixing in the vicinity of the discharge jets facilitated rapid cooling of condenser-passed water.

Secchi disc depths ranged from less than 1 m to over 12 m, with highest values occurring in summer. There was no evidence of decreased Secchi disc depths in the vicinity of the thermal plume.

Monthly surveys conducted in 1977 (April to December) and 1978 (April to November) provide information on zooplankton distributions over the 250 km^2

survey area during plant operation. Seasonal and spatial zooplankton distribution patterns (numbers, percent composition, biomass) generally were similar to those observed in preoperational years. No evidence of gross alterations in zooplankton populations in the vicinity of the thermal plume was found on 16 of the 17 cruises. However, during the August 1978 cruise, *Bosmina longirostris* occurred in densities of 294,300/m^3 over the discharge jets in comparison to densities of 27,300/m^3 and 9,000/m^3 less than 1 km south and north of the discharge jets. The reason for this is unknown.

Two new species occurrences were noted. *Daphnia parvula* was observed at a few stations in May 1978 but was not observed in later months in 1978. This species typically is associated with ponds and small lakes in more southern locales. *Daphnia pulex* was observed at several stations during the October and November 1978 cruises. This species is found in more eutrophic regions of the Great Lakes: its occurrence may be indicative of increased eutrophication of the southern basin of Lake Michigan. *Mesocyclops edax*, a cyclopoid copepod which was collected infrequently up to 1977, occurred in relatively high numbers in the October and November 1978 cruises. Like *Daphnia pulex*, this species occurs in more mesotrophic and eutrophic regions of the Great Lakes. Furthermore, both species are relatively large zooplankters and are particularly susceptible to fish predation. Increased concentrations of both species also may be related to changes in the fish community structure in southeastern Lake Michigan.

As in the previous report (Evans *et al*. 1978), variations in zooplankton distribution over the survey grid were investigated using principal component analysis. Depth was identified as the most important factor in the overall

abundance patterns of zooplankton. The major survey grid, consisting of 30 stations and sampled during April, July, and October of each year, was divided into four depth-related regions: an inner region between the 5-m and 10-m depth contours, a middle region between the 10-m and 20-m depth contours, an inner offshore region between the 20-m and 30-m depth contours, and an outer offshore region extending beyond the 30-m depth contour. During warm months of the year, zooplankton tended to be least abundant in the inshore region and to increase in abundance with depth out to the 20-m to 30-m depth contour: abundances levelled off or decreased slightly with greater distance from shore. Zooplankton differed in composition with distance from shore (depth). The inshore region was dominated by small zooplankton while larger cladocerans and copepods tended to increase in dominance with increasing station depth. During the cooler months of the year, zooplankton tended to be most abundant in shallower areas of the survey grid. There were relatively minor differences in composition with respect to station depth.

To compare preoperational and operational zooplankton densities, the survey grid was further divided into eight zones. The inshore and middle regions were each divided into three zones - a plume zone extending 1 km north and south of the plant site, and north and south control zones. Within the inshore and middle plume zones, seasonal abundance patterns of major taxa were generally similar during preoperational and operational years. For the most part, the range of population densities observed in the preoperational period were not exceeded in the operational period. Exceptions were adult Diaptomus spp., Eurytemora affinis copepodites, and Eubosmina coregoni whose maximum attained abundance in the operational period was 1.5 to 5 times that observed in the preoperational period. Such differences were observed in other zones of the

survey grid and probably were related to factors such as eutrophication or changes in fish community structure which affected the entire survey grid.

Comparisons of zooplankton densities between the preoperational (1971-1974) and operational (1975-1978) periods by major survey month (April, July, October) and by zone (a total of eight) indicated that many taxa occurred in statistically significant different concentrations before and during plant operation. In April, zooplankton tended to be more abundant in the operational period with the greatest increase in numbers associated with nauplii, immature and adult *Diaptomus* spp., immature *Cyclops* spp. copepodites, and *Limnocalanus macrurus* copepodites. In July, zooplankton taxa tended to be less abundant in the operational period with the exception of *Daphnia* spp., which were more abundant. In October, zooplankton tended to be more abundant in the operational period with increased abundances of nauplii, immature *Cyclops* spp. and *Diaptomus* spp. copepodites, and *Eubosmina coregoni*. However, *Daphnia* spp. and adult *Cyclops* spp. tended to be less abundant.

While differences in zooplankton abundance were detected more frequently in the inshore and middle plume zones than in the six control zones, differences of similar magnitude were observed in plume and control zones. The preoperational and operational differences in zooplankton abundances require further investigation. Differences may be related to increased eutrophication of the southern basin, greater phytoplankton standing stocks, summer increases in the numbers and dominance of bluegreens, and changes in the fish community. As the preoperational and operational differences were widespread and not localized in the immediate discharge area, they cannot be attributed to the direct power plant impact on zooplankton populations in the vicinity of the plant.

Zooplankton mortalities as a result of plant passage were low in most months, averaging 9.1% in the intake forebay and 10.3% in the discharge forebay waters. January 1978 intake mortalities approached or exceeded 50%. Similarly, high intake mortalities were observed in January 1976 and may be related to resuspension of detrital zooplankton in the vicinity of the intakes. Discharge mortalities were high in September 1978 when discharge water temperatures reached 35°C.

Statistical analyses were stratified by month and taxa to investigate whether or not zooplankton mortality was significantly greater in discharge than in intake waters. Several significant differences were detected, with the majority occurring in August and September 1978 when discharge waters approached or exceeded 32°C. Further analyses were performed using mortality data for the 1975 to 1978 period. For the 0-hour and 6-hour incubation periods, calanoid copepods were the major taxa exhibiting significantly higher discharge mortalities than intake mortalities, although *Daphnia* spp. and *Eubosmina coregoni* also exhibited significant differences. The mean monthly difference between intake mortalities and Unit 1 discharge mortalities, calculated for taxa which exhibited significant differences in mortalities, ranged from 2.6% to 7.3%. Overall, mortalities were not significantly related to discharge water temperature nor to delta-T. However, the data suggest that mortalities would increase substantially were discharge water temperature to exceed 35°C.

Thousands of zooplankton passed through the plant each second. The estimated biomass entrained each month ranged from 20 kg dry weight in February 1978 to 39,718 kg dry weight in August 1978, and averaged 8,819 kg/month. The estimated maximum biomass loss (based on the assumption that discharge mortality represented a probable upper limit of mortality loss) ranged from 11 kg/month (February 1978) to 5,021 kg/month (December 1978), and averaged 1,232 kg/month.

More zooplankton were entrained in the 1977 to 1978 period than in the 1975 to 1976 period due to the greater abundance of zooplankton and higher cooling-water utilization rate in 1977 and 1978. It is unlikely that the presence of detrital zooplankton produced as a result of plant passage adversely affected water and sediment quality in the discharge area. The nearshore region is not an area of net deposition, and much of this material probably was transported to deeper regions of the lake.

A heterogeneity study was conducted in the intake and discharge forebays to determine the representativeness of sampling locations. The intake location MTR1-5 provides a statistically representative sampling location for the intake forebay. In addition, the long-term (1975 to 1978) entrainment data were analyzed to determine abundance trends between intake and discharge sampling locations. Examination of all abundance estimates made during this period for the intake forebay and Unit 1 discharge forebay indicated that zooplankton concentrations were significantly higher in the intake forebay. Further analyses, stratified by year, indicated that only in 1976 were abundance estimates significantly higher in the intake forebay than in Unit 1 discharge forebay. As Unit 2 was operational for a relatively short time period, the data base for such analyses was smaller. There were no statistically significant differences in zooplankton abundances between Unit 2 discharge forebay and the intake forebay and between Units 1 and 2 discharge forebays.

Field survey data and entrainment data were analyzed to determine the representativeness of the power plant as a sampling location for zooplankton populations within the 10-m depth contour. The correlation between taxa abundance in entrainment and lake collections was significant for total zooplankton and most of the seasonal dominants. The exceptions were immature and adult *Cyclops* spp. copepodites. In addition to inhabiting the water column,

these taxa have epibenthic affinities and live in high concentrations in close proximity to the sediments in addition to inhabiting the water column. Storm activity may resuspend a greater fraction of the epibenthic population in some months than in others. Alternatively, epibenthic species may exhibit seasonal migratory behavior, with a greater fraction of the population entering the water column in some months than others. Such factors could account for the poor correlation between entrainment and lake population estimates. Overall, the analyses suggest that entrainment sampling can provide reliable zooplankton population estimates for the inshore region of the survey grid.

An intensive study mapped zooplankton distributions adjacent to and within the 1-m and 3-m plume on 15 June 1977. Large increases in zooplankton populations were observed in the 1-m plume which persisted up to several hundred meters from the discharge jets. Vertical displacement of zooplankton over the discharge jets was identified as the most significant factor producing these patterns. An upwelling which occurred during the study blurred the thermally-detectable plume, although the plume was biologically detectable over a wider area. The vertical displacement of zooplankton in the vicinity of the discharge jets probably does not severely stress zooplankton, although such displaced and disorientated zooplankton may be more susceptible to fish predation.

This report interrelates the results of several studies conducted at the Donald C. Cook Nuclear Plant in 1977 and 1978 and utilizes the 1975 and 1976 operational and the 1971 to 1975 preoperational data. It provides an overview of plant operation effects over 250 km^2 area of southeastern Lake Michigan. Some of the program limitations are discussed, and areas which require further investigation are suggested.

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INTRODUCTION

New technological developments, increasing energy demands, and decreasing supplies of conventional fuels led to acceptance of nuclear power plants as economically feasible suppliers of energy in the 1960s and early 1970s. Although a number of small plants in the hundred megawatt capacity range had been in operation since the 1950s, it was not until the late 1960s that both the number and size of nuclear plants increased substantially (Sorge 1969). About this time, environmental pollution became a subject of immense public concern. As a result of these factors, both nuclear and conventionally fueled power plants became subject to more rigorous licensing requirements. One of these, section 316(a) of the Federal Water Pollution Control Act, requires that the thermal component of plant effluents be such that it will "assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on that body of water." The other, section 316(b), requires application of the best technology available to cooling water intake structures so that the location, design, construction, and capacity of such structures will minimize adverse environmental impacts. This report addresses the effects of the operation of the Donald C. Cook Nuclear Power Plant cooling water system on the zooplankton of southeastern Lake Michigan. The report focuses on the 1977 and 1978 period but also considers the 1975 and 1976 operational period.

The Donald C. Cook Plant is a two-unit plant which, at full operational capacity, produces 2,200 MWe. The plant is one of the largest of the nearly fifty nuclear and coal-fired plants on Lake Michigan. The Zion Plant, located north of Chicago, is the only other similar-sized operational plant.

At full operational capacity, the Donald C. Cook Plant utilizes approximately 6,300 m^3 of water each minute for its once-through cooling system. This rate is equivalent to the mean annual flow of any one of the four largest rivers (Fox, St. Joseph, Grand, Menominee) discharging into Lake Michigan (U. S. Department of the Interior 1968). Zooplankton passing through the plant are exposed to temperature increases of up to 12 C° above ambient for a period of approximately 3 minutes. Calculations of thermal dissipation along the centerline of the plume produced by Unit 1 (United States Atomic Energy Commission 1973) provide an estimate of plume-entrained zooplankton exposure times to various Δ-T's. Using these calculations and applying them to two-unit operation, zooplankton exposure times to temperatures 2.8 C° (5 F°) above ambient are on the order of 20 minutes while exposures to temperatures 1.7 C° (3 F°) above ambient are on the order of 142 minutes.

A large body of literature has accumulated which documents the effects of thermal discharges on zooplankton communities in a number of fresh, brackish, and marine water habitats. The subject is complex and factors such as zooplankton composition, discharge water temperature, Δ-T, season, plant design, morphometry of the receiving water body, and survey grid design are all crucial in determining whether or not changes in zooplankton populations due to plant operation are detected. In general, power plants operating at lethal temperatures and discharging comparatively large volumes of water into small receiving water bodies do have detectable effects on zooplankton populations (Zhitenjowa and Nikanorow 1972). Conversely, power plants operating at sublethal temperatures and discharging comparatively small volumes of water into large receiving water bodies do not have any immediately detectable effect on

zooplankton populations (Heinle 1969, Mathur et al. 1980). The Donald C. Cook Nuclear Plant is in this second category (Evans et al. 1978, this report).

The upper lethal temperature limit for most aquatic organisms has not been determined. Drost-Hansen (1969) suggested that it is probably in the mid-30s °C range. Laboratory studies using *Cyclops* spp. and *Diaptomus* spp. (Industrial Bio-Test Laboratories, Inc. 1974a) and field studies (Reeve 1970, Davies and Jensen 1974) tend to support this hypothesis. Some zooplankton which can live and reproduce at temperatures in the lower 30s °C experience a high incidence of shock after a few minutes exposure to temperatures an additional few degrees higher (Brown and Crozier 1927-1928). Upper lethal temperatures depend upon a number of factors including acclimation temperature and Δ-T (Industrial Bio-Test Laboratories, Inc. 1974a, Kwik and Dunstall 1981).

Zooplankton mortalities during condenser passage are minimized when discharge water temperatures do not exceed 35 C° and the Δ-T 15 C° to 20 C°. Plume entrainment mortalities are minimized when heated discharge waters are rapidly cooled. Mortalities may be high in long, narrow receiving water bodies such as discharge canals and river channels (Davies and Jensen 1974, Zhitenjowa and Nikanorow 1972). Subsurface discharge jets (as at the Donald C. Cook Nuclear Plant) increase the rate at which discharge water is cooled and can substantially reduce the effects of heated effluents on the receiving water body (Eiler and Delfino 1974). In grossly polluted waters or in areas where significant portions of the receiving water body are heated, the construction of cooling towers may be the only viable alternative (Ross and Whitehouse 1973).

Exposure to temperatures less than 35 °C, while generally non-lethal, affects a number of physiological processes including growth, reproduction, feeding, and longevity (Brown 1926-1927, Brown and Crozier 1927-1928,

MacArthur and Baillie 1929a and b, Pratt 1943, Green 1956, Hall 1964, Comita 1968, Naylor 1965, Heinle 1969). If exposure times are sufficiently long, changes in zooplankton physiology may result in changes in zooplankton community structure and biomass (Patalas 1970, Lanner and Pejler 1973, McMahon and Docherty 1975). Such alterations have been detected for temperatures in the mid-20s °C and have been limited to small bodies of water (experimental chambers, small lakes) where the cooling rate of heated water and the transport of zooplankton away from the heat source have been low. Power plants operating on large bodies of water such as Lake Michigan generally have had no detectable effect on zooplankton communities (Industrial Bio-Test Laboratories, Inc. 1974b and c and 1975, Texas Instruments Inc. 1975, Evans et al. 1978).

This report presents the results of studies conducted in 1977 and 1978 evaluating the effects of the operation of Unit 1 and Unit 2 of the Donald C. Cook Nuclear Power Plant on zooplankton populations in southeastern Lake Michigan. Although our studies began in 1969, it was not until February 1975 that Unit 1 became operational and not until April 1978 that Unit 2 became operational. This is the second operational report and the first to address the effects of two-unit operation.

The main body of the report consists of five sections. The first section describes zooplankton distributions over the survey area in 1977 and 1978 and the associated thermal and Secchi disc characteristics of the water. In the second section, comparisons are made of the seasonal patterns of zooplankton abundance in the immediate discharge area before and during plant operation. Furthermore, statistical comparisons are made of zooplankton abundances in the preoperational and operational periods for plume and control zones of the survey grid.

The third and fourth sections focus on the direct effect of condenser passage. In section three, mortality levels of zooplankton passing through the plant are presented and related to water temperature (intake, discharge, and Δ-T). These data are statistically analyzed to investigate whether or not plant passage significantly affects zooplankton mortality. In the fourth section, the numbers and biomass of zooplankton passing through the cooling system and the numbers and biomass killed are estimated. The results of a heterogeneity study of zooplankton abundances in the forebay are reported in addition to results from a study comparing zooplankton population characteristics as estimated from lake and entrainment sampling. The fifth section presents the results of an intensive study of zooplankton distributions within and adjacent to the thermal plume and shows the extent of changes which can occur. This study was conducted in June 1977 during an upwelling and contrasts with an earlier study conducted in September 1976 (Evans _et al_. 1978). A concluding section interrelates the results of the zooplankton studies, discusses some of the limitations in the monitoring program, and suggests areas which require further investigation.

SECTION 1

THE SEASONAL AND SPATIAL DISTRIBUTIONS OF ZOOPLANKTON DURING THE 1977 AND 1978 SURVEY CRUISES

INTRODUCTION

Zooplankton are weakly motile animals carried by water currents from one area to another. They are smaller than most sedentary benthos and the more powerfully swimming fish. Unlike most phytoplankton, zooplankton are capable of movement and actively maintain themselves at particular depths in the water column. Both vertical and horizontal movements are related to behavioral functions (feeding, reproduction, predator avoidance).

Zooplankton are collected by a variety of techniques, most of which involve filtration. In Lake Michigan, zooplankton collected with a 158-μm mesh net generally range in size from 0.2 to 2.0 mm. Crustaceans and, in particular, copepods and cladocerans, dominate these collections. Rotifers are the third major component of Great Lakes zooplankton and are collected most efficiently by nets 76-μm in mesh size and smaller. Collection of rotifers was initiated in 1979 and will be discussed in a later report.

Zooplankton generation times vary from a few days for cladocerans and certain copepods at optimal temperatures of 20°C to up to a year for hypolimnetic copepods such as *Limnocalanus macrurus*. Cladocerans reproduce parthenogenetically with preadults (morphologically similar to adults) released every couple of days under optimal conditions. Copepods reproduce sexually with eggs hatching into nauplii, proceeding through six naupliar stages and six copepodite stages with the sixth being the adult.

Abundance varies seasonally in the survey area from less than $1,000/m^3$ (late winter minimum) to over $200,000/m^3$ (mid-summer maximum). Copepods are the numerically dominant form during winter and spring while cladocerans generally dominate during the summer and autumn. Spatial variations in abundance, while smaller than temporal variations, are significant. Factors which have been implicated as significant in producing spatial variability include phytoplankton abundance and composition, fish predators, invertebrate predators, and intraspecific competition. Physical events such as upwellings can alter zooplankton assemblages in an area in a matter of hours, replacing epilimnetic zooplankton with metalimnetic and hypolimnetic species.

As is common to all organisms, zooplankton species have a particular set of environmental conditions which are optimal for their survival and successful competition with other species. Zooplankton communities change as water bodies undergo natural evolution from young, oligotrophic waters to more mature, eutrophic systems such as marshes and wetlands. Such events are gradual, involving time scales ranging from hundreds (small lakes) to millions (large tectonic lakes such as Lake Baikal) of years. Recently, as a result of man's activity and useage of lakes, eutrophication processes have accelerated. This accelerated or "cultural eutrophication," with its natural ecological counterpart, is relatively predictable in its biological effects. Other types of pollution, such as pollution by organic compounds (e.g., PCBs), heavy metals, and increased acidity, have few counterparts in the natural system. Consequently, it is difficult to predict the ecological effects of these types of pollution.

In the late 1960s and early 1970s there was concern that increasing power plant construction on Lake Michigan shores, with the ensuing substantial usage of lake water for condenser cooling, would have detrimental effects on lake biota, including the zooplankton. Monitoring programs were designed to determine these effects, with the size of the program a function of power plant size. The Donald C. Cook Nuclear Power Plant, one of the largest plants on Lake Michigan, has had a particularly large monitoring program. The lake sampling program, which includes a large survey grid and several years of preoperational (1969-1974) and operational (1975-1981) monitoring, was designed to detect power-plant related changes in zooplankton assemblages over a substantial area of the lake.

Preoperational studies have determined the major limnological features of this area. Water tends to flow in a northerly direction, parallel to shore, but does flow in other directions depending on meteorological events. The Michigan City-Benton Harbor eddy lies in the outer half of the survey area during part of the spring, summer, and autumn (Ayers et al. 1958, Ayers et al. 1967). Nutrient-enriched water enters the survey grid from the north (St. Joseph River) and from the south. Enriched water also enters the survey grid from the Bridgman sewage plant (3 km south of the plant site) and from streams south of Warren Dunes State Park. Differences in water flow and chemistry have resulted in both along-shore and inshore-offshore differences in sediment composition (Rossmann 1975).

Macrobenthic populations vary in abundance and composition with distance from shore and, to a lesser extent, along shore (Mozley 1973 and 1974,

Johnston 1973). Similar differences occur in fish populations inhabiting southeastern Lake Michigan (Wells 1968, Jude et al. 1975).

Plankton exhibit less consistent along-shore differences in abundances than do the benthos and fish. This is because plankton are carried through the survey grid by lake currents which vary in speed and direction under various meteorological and lake conditions. Under average lake currents of 6.1 cm/sec (Ayers et al. 1958), plankton are carried through the survey grid in a matter of days. Phytoplankton populations (collected from 1 m depth) exhibit only slight inshore-offshore differences in abundance (Ayers 1975) while zooplankton (collected from the entire water column) exhibit pronounced inshore-offshore differences in abundance (Evans et al. 1980) and biomass (Hawkins and Evans 1979) in most months.

This section describes zooplankton distributions in 1977 and 1978 over the survey grid. It also presents the results of additional analyses of depth-related differences in zooplankton assemblages. The thermal characteristics of the water column, the location of the thermal plume, and Secchi disc depths are presented for each cruise.

MATERIALS AND METHODS

The Survey Grid

The survey grid (Fig. 1) extends 11 km north and south of the plant site and 11 km offshore. The closest power plant south of the Donald C. Cook Nuclear Power Plant is the Michigan City Generating Station (34 km), a 203 MWe plant which utilizes both a cooling tower and once-through cooling. To the north

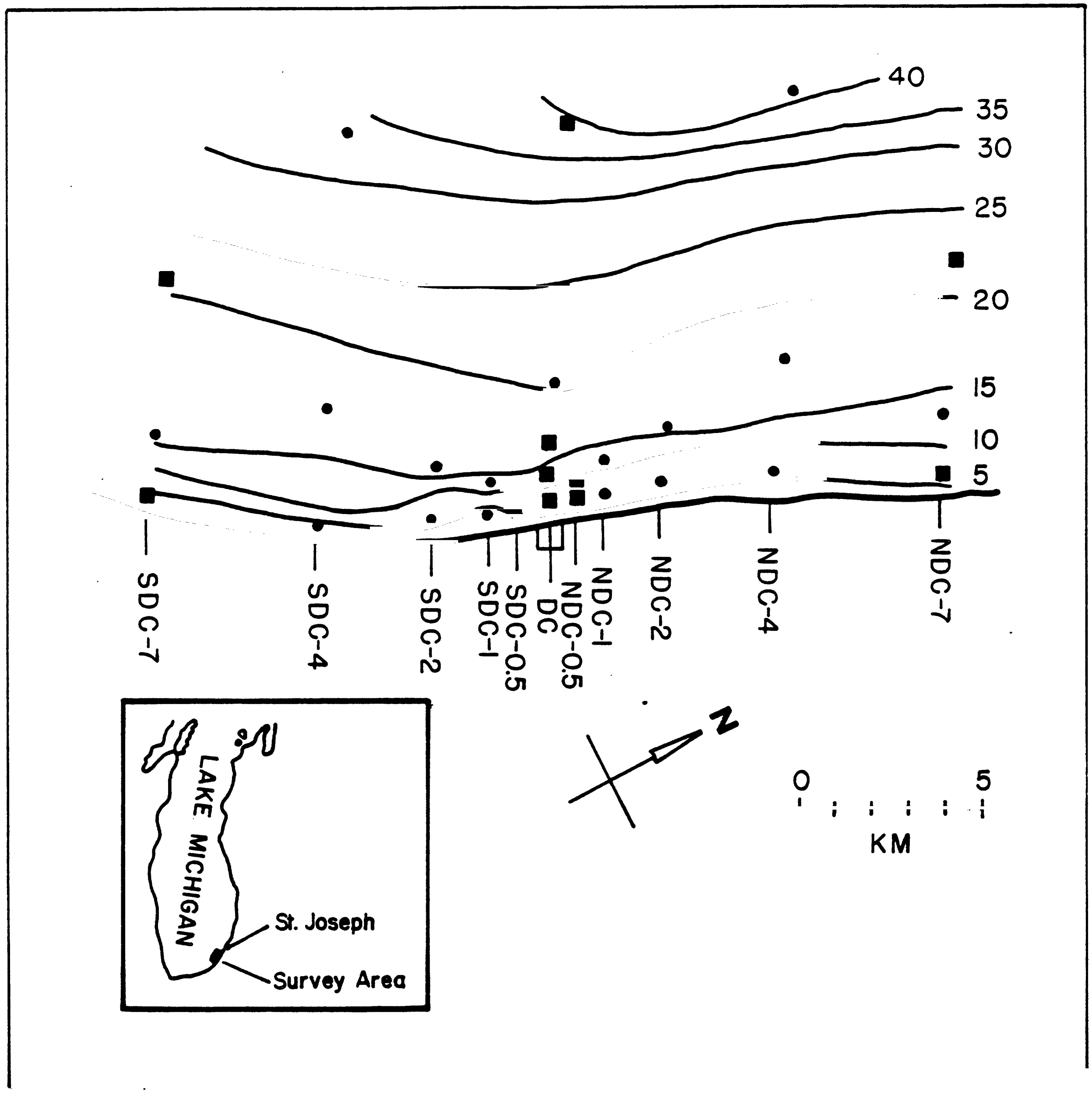

FIG. 1. Station locations for the major surveys. Squares indicate the subset of short survey stations. Depth contours are in meters.

(55 km) is the Palisades Nuclear Power Plant, an 811 MWe facility (Krezoski 1969) which now employs cooling towers.

Major surveys and short surveys (Fig. 1) are conducted monthly from April through November. Major surveys presently consist of 30 stations and provide detailed information on zooplankton assemblages during the spring (April), summer (July), and autumn (October). Short surveys presently consist of 14 stations and provide information on zooplankton population dynamics during the intervening months.

The original (1970) survey grid consisted of 46 stations. The current monitoring program consists of 14- or 30-station subsets of the original grid. A two-part numbering system was used to name each station. The first part, DC, NDC x or SDC x refers to the location of a transect relative to the plant site. The DC transect extends directly offshore from the plant, and the NDC x and SDC x transects are respectively 0.5, 1, 2, 4, or 7 miles north or south of the plant site. The second part of each station name designates the station number in a transect series. For example, DC-1 is the first station along the DC transect (and closest to shore) while DC-6 is the sixth station along the transect. DC-6 is as far offshore as NDC 4-4, the fourth station in the NDC 4 transect.

For the major survey cruise grid (Fig. 1) six stations along the DC transect have been retained, along with Stations 1 and 2 of the original three of the NDC 1 and SDC 1 transects, Stations 1 and 3 of the original three of the NDC 2 and SDC 2 transects, Stations 1, 3, and 4 of the original four of the NDC 4 and SDC 4 transects, and Stations 1, 3, and 5 of the original five of the

NDC 7 and SDC 7 transects. The short survey grid consists of a subset of the major survey grid.

Station depths range from 4 m to over 40 m and increase with distance from shore (Fig. 1). The three intakes utilized by the power plant are located approximately 690 m offshore (between stations DC-1 and DC-2) in 7.3 m of water. The intakes form the apexes of a 75-m equilateral triangle. Two discharge pipes return heated water to the lake, with the northern pipe servicing Unit 1 and the southern pipe Unit 2. The two discharges are located approximately 380 m offshore (Station DC-1) in 5.5 m of water and are 100 m apart.

Physical Measurements

Surface water temperatures were measured at each station with a thermometer immersed in a bucket of freshly collected water and/or with a YSI thermistor probe suspended a few centimeters below the water surface. Temperature-depth profiles were determined with an electronic bathythermograph and a chart recorder. Temperature could be read with a precision of $\pm$ 0.5C° and depth with $\pm$ 0.25 m precision. At each station, both ascending and descending traces were recorded and the average calculated. Traces were not obtained at all stations due to malfunctions in the electronic bathythermograph. At those times, a 61.0-m mechanical bathythermograph was used.

Secchi disc depths were measured using a (20.3-cm) 8-inch diameter white disc. Water color also was noted. Data are missing from stations sampled after sunset; for the five cruises for which this occurred, generally only one or two stations were affected.

Zooplankton Sampling Methods

Zooplankton were collected at each station with a 50-cm diameter net (156-μm aperture mesh). A calibrated flowmeter mounted in the mouth of the net measured the volume of water filtered during each vertical haul. Three net hauls were made at each station from as close to the bottom as possible (generally 1 m with the winch operator "feeling" the net touch bottom) to the surface. The flowmeter was read, the outside of the net hosed down, and the contents of the plankton bucket transferred to a labelled jar and preserved with Koechie's fluid, a sugar-formalin solution (2.3 kg sugar dissolved in 2 L of formaldehyde, and 8 L of water). In two cruises (October 1977 and April 1978), bad weather prevented the collection of the third replicate net haul.

Counting Techniques

In the laboratory, zooplankton in the first two replicate samples were counted. Occasionally, when there was poor agreement between the results of the first and second sample counts, the third replicate sample was examined. This occurred on fewer than five occasions in 1977 and 1978.

Each sample was subdivided as many times as necessary in a Folsom plankton splitter to give two subsamples of 350 to 700 organisms each. A third subsample of 700 to 1,000 organisms was examined for rare taxa (less than 40 animals in the summed subsample counts). Cladocerans and adult copepods were identified to species level at all survey stations. Adult copepods were distinguished by sex at all stations. Immature copepodites were identified to genus while nauplii were combined as a group. Taxonomic keys referred to included Pennak (1963),

Deevey and Deevey (1971), Brooks (1957, 1959), Wilson (1959), Yeatman (1959), Wilson and Yeatman (1959), and Tressler (1959).

Zooplankton were enumerated in a circular counting dish using a microscope at a magnification of 20 to 140x. A compound microscope was used to verify certain species identifications and to identify species whose occurrences in the survey area had not been noted previously. In these instances, past collections were re-examined for the presence of these species.

Dry Weight Determinations

Each month, triplicate weight measurements were made with a Cahn electrobalance (accurate to $\pm$ 0.5 μg) for groups of 3 to 30 preserved animals from the numerically dominant taxa. Before weighing, the animals were washed in distilled water, placed in preweighed aluminum boats (0.5-cm diameter), and dessicated for at least 48 hours over silica gel absorbent at room temperature.

Biomass was determined for most taxa from samples collected at DC-1 and DC-6. When taxa were rare at one of the two stations, biomass estimates were based on determinations made at only one station. A few taxa, generally less than 5% of total zooplankton, were so rare that their dry weights were not determined. We did not observe any consistent differences in mean dry weight of the various taxa between the two stations, so we averaged the results to obtain a mean biomass estimate for each taxon over the survey grid during a particular cruise. An estimate of zooplankton standing stock (mg dry weight/m^3) was calculated by summing the product of the mean biomass (μg/individual zooplankton taxon) and the density estimate (number/m^3) for each taxon. The mean dry weight per individual at each station was calculated by dividing total zooplankton standing

stock (mg dry weight/m^3) by the station mean zooplankton density estimate (number/m^3).

Principal Component Analyses

We have used principal component ordinations on the 1972-1976 field survey data to identify groups of stations with similar zooplankton abundances and species composition. Stations generally clustered together along a station depth gradient, suggesting that factors related to depth are important in determining zooplankton distributions over the survey area (Evans *et al.* 1980). Stations within or close to the thermal plume generally clustered with control stations of similar depths.

We have performed similar ordinations using the April, July, and October 1977 and 1978 major cruise data as well as the December 1977 short survey data. When possible, we have used the same taxa in a seasonal analysis as used in previous analyses. However, year-to-year differences in the abundances of rare taxa have caused minor alterations in the taxa selected for the April and July 1977 and 1978 analyses.

The analyses were performed using the variance-covariance matrix of the log-transformed (numbers/m^3 + 1) taxa data. Generally if a taxon accounted for at least 1% of the zooplankton at several stations for a month, it was used in an analysis. Six taxa were used for the April analysis; 12 for the July 1977 analysis; 11 for July 1978; and 13 for the October analysis. Eleven taxa were used for the December 1977 analysis. Correlations between the principal components and the log-transformed original variates were performed to assist interpretation of the principal components. The analyses were performed using

the Michigan Interactive Data Analysis System (MIDAS), a statistical package on The University of Michigan computing system.

RESULTS

Survey Cruise Characteristics

14 April 1977

The 14 April 1977 cruise was conducted during a moderately cool spring. Surface water temperatures ranged from 2.2°C to 10.2°C. The thermal bar was approximately 6 km offshore. The thermal plume was small and weakly defined (Fig. 2a). Secchi disc depths (Fig. 3a) ranged from 1.7 to 5.7 m. Water color was gray-green.

Nauplii accounted for more than 50% of the zooplankton and occurred in concentrations ranging from 3,300-16,500/m^3 (Fig. 4). Adult *Diaptomus ashlandi*, *D. sicilis*, and *Cyclops bicuspidatus thomasi* were the numerically dominant species followed by *D. minutus*, *D. oregonensis*, and *Limnocalanus macrurus*. Immature *Cyclops* spp. and *Diaptomus* spp. copepodites (Fig. 4) were less abundant than adults. While most copepod taxa occurred in higher abundances in the shallower areas of the survey grid, immature *Cyclops* spp. copepodites (Fig. 4) were most abundant in deeper waters. These immatures probably were remnants of the overwintering immature copepodite population rather than immatures produced as a result of spring reproduction. Development to the adult stage probably occurred at a more rapid rate for copepodites inhabiting the shallower, warmer, and more productive areas of the survey grid. Immature *Limnocalanus macrurus* copepodites occurred in approximately equal concentrations as adults.

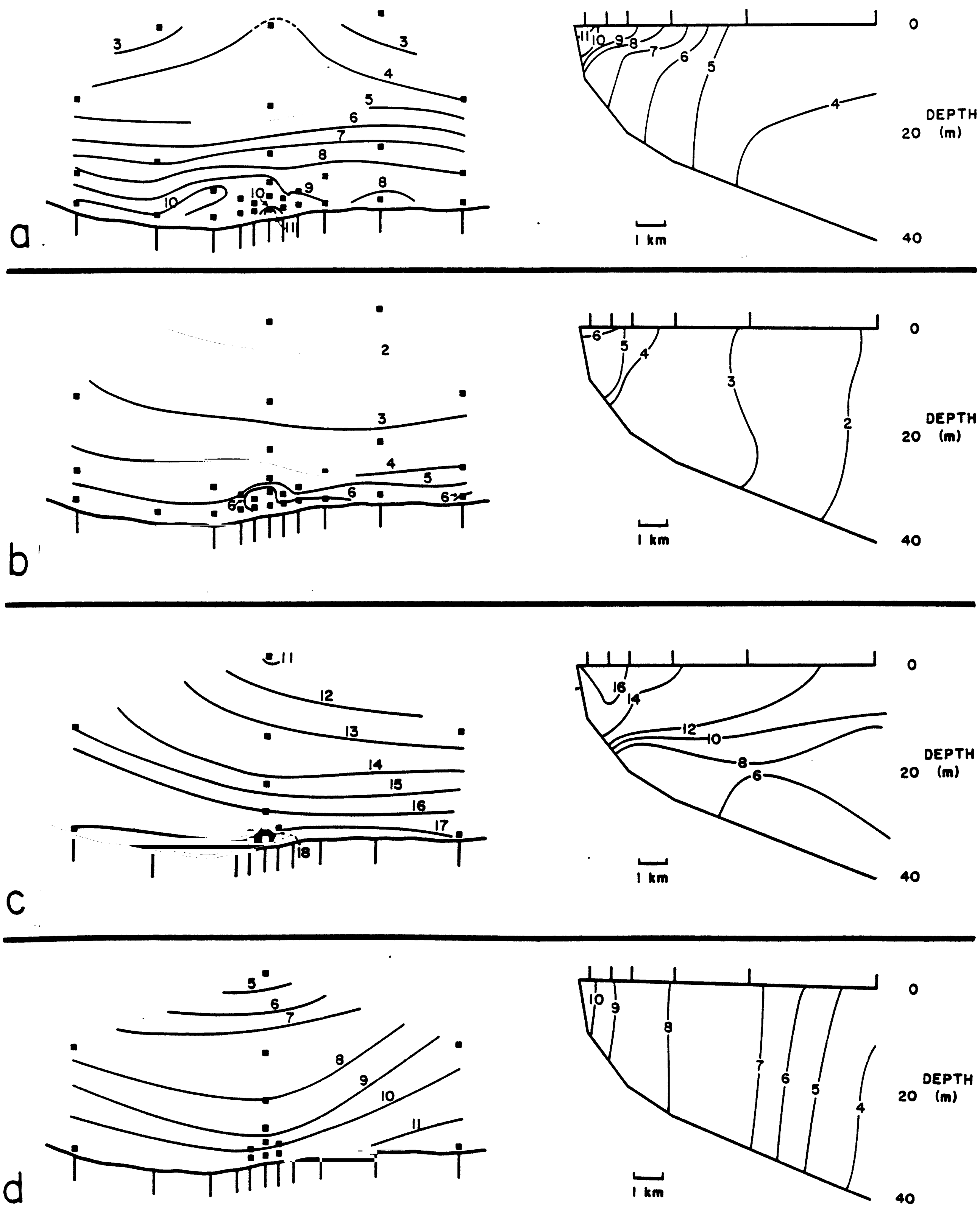

FIG. 2. Surface water temperature and temperature-depth profiles along the DC transect on a) 14 April 1977, b) 12 April 1978, c) 18 May 1977, d) 12 May 1978,

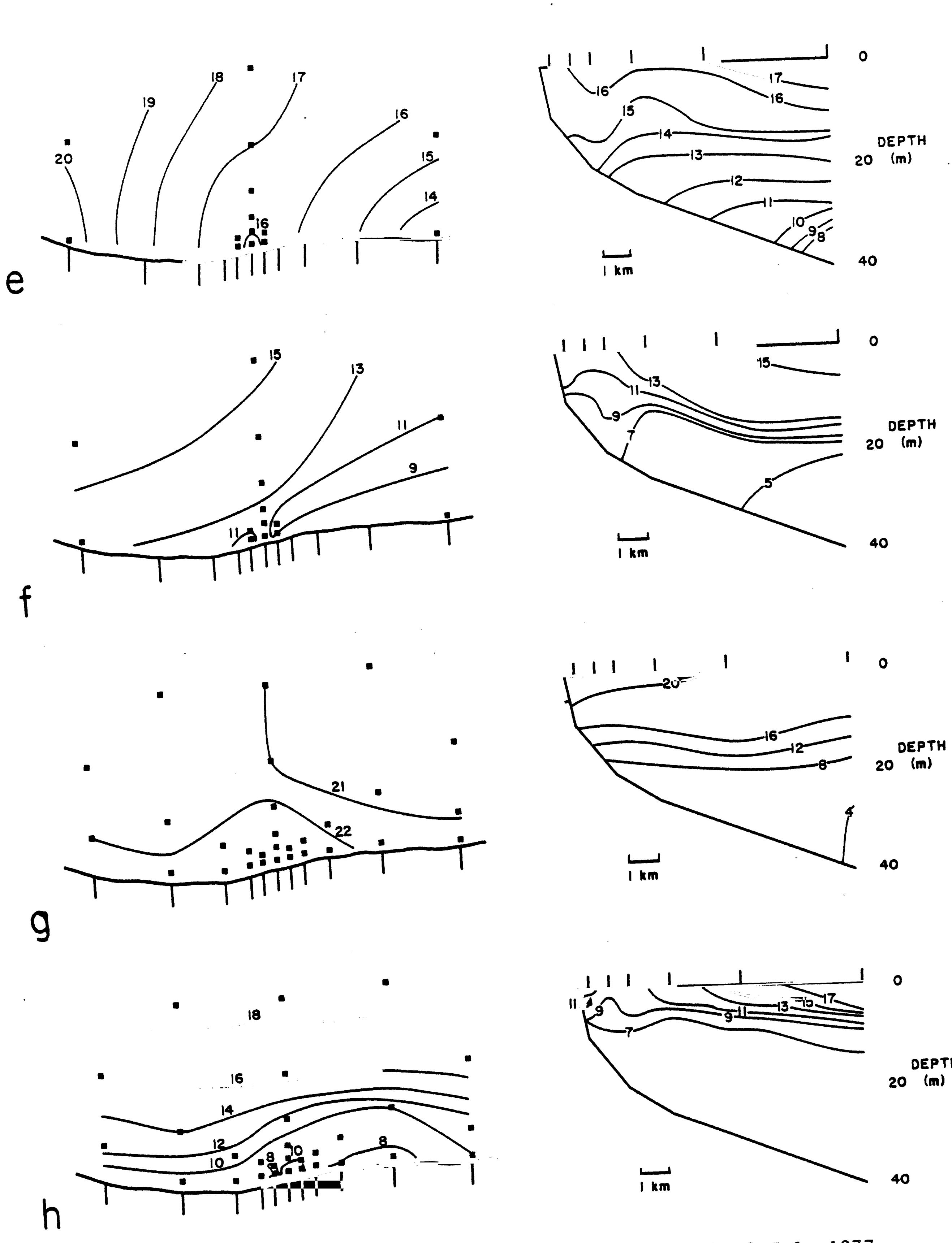

FIG. 2. Continued. e) 16 June 1977, f) 15 June 1978, g) 13 July 1977, h) 12 July 1978,

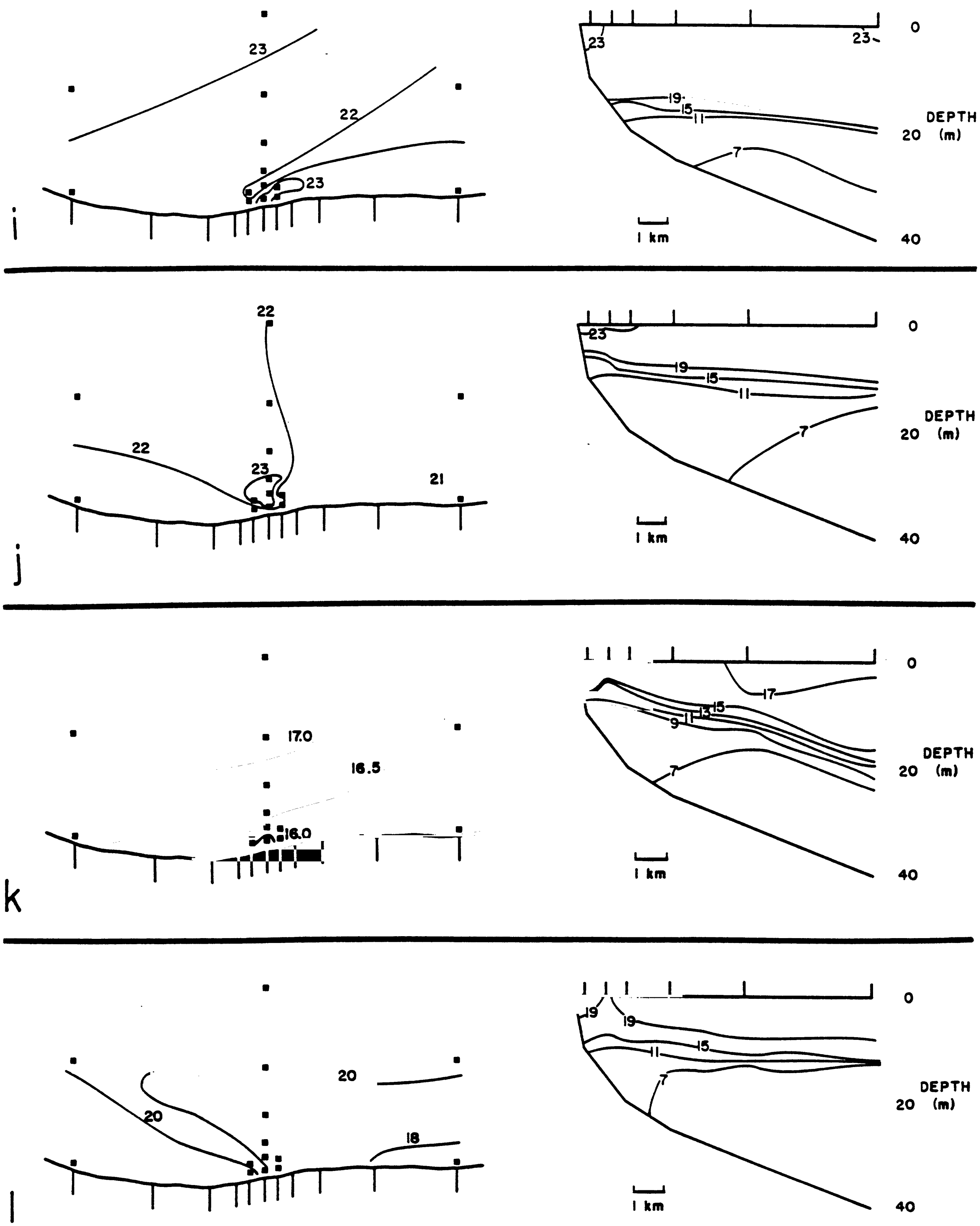

FIG. 2. Continued. i) 10 August 1977, j) 10 August 1978, k) 14 September 1977, l) 14 September 1978,

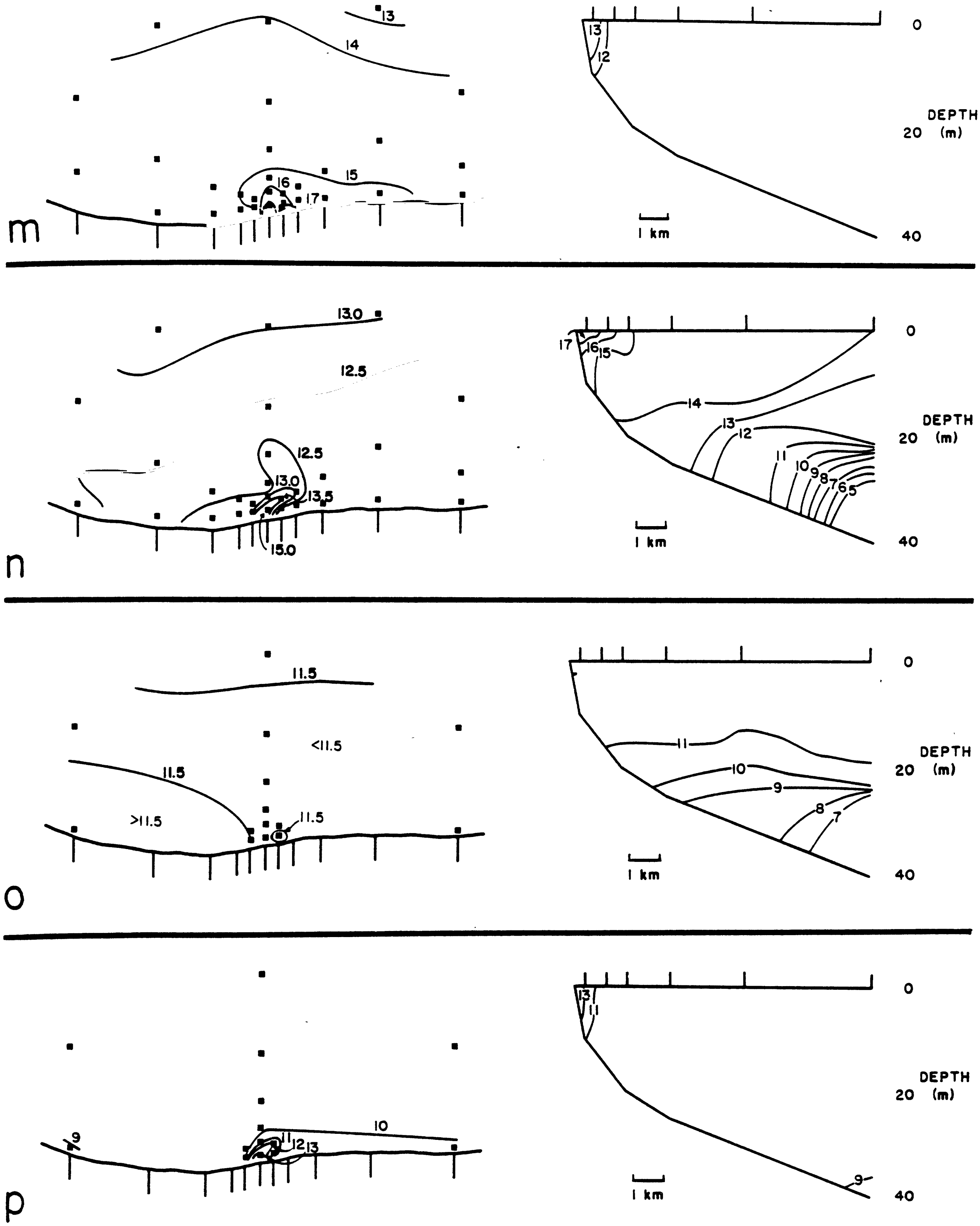

FIG. 2. Continued. m) 14 October 1977, n) 11 October 1978, o) 9 November 1977, p) 16 November 1978,

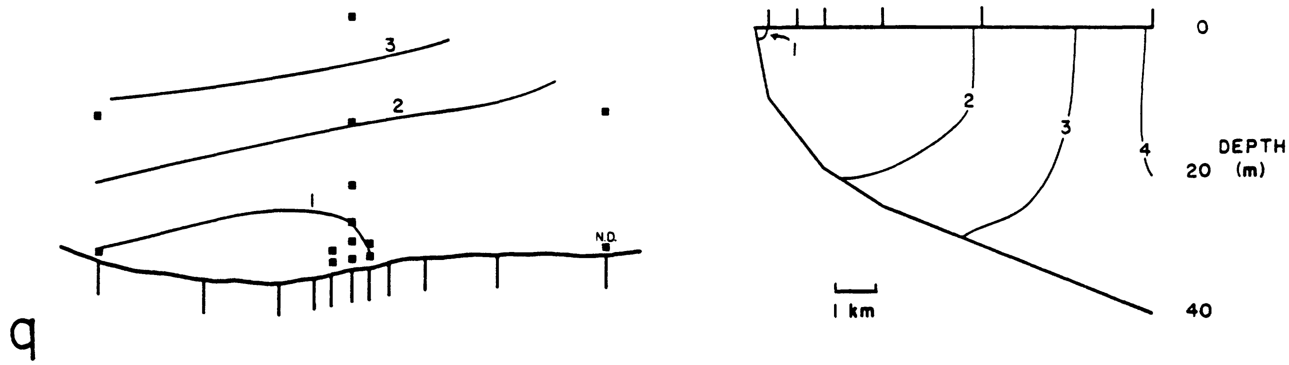

FIG. 2. Concluded. and q) 15 December 1977.

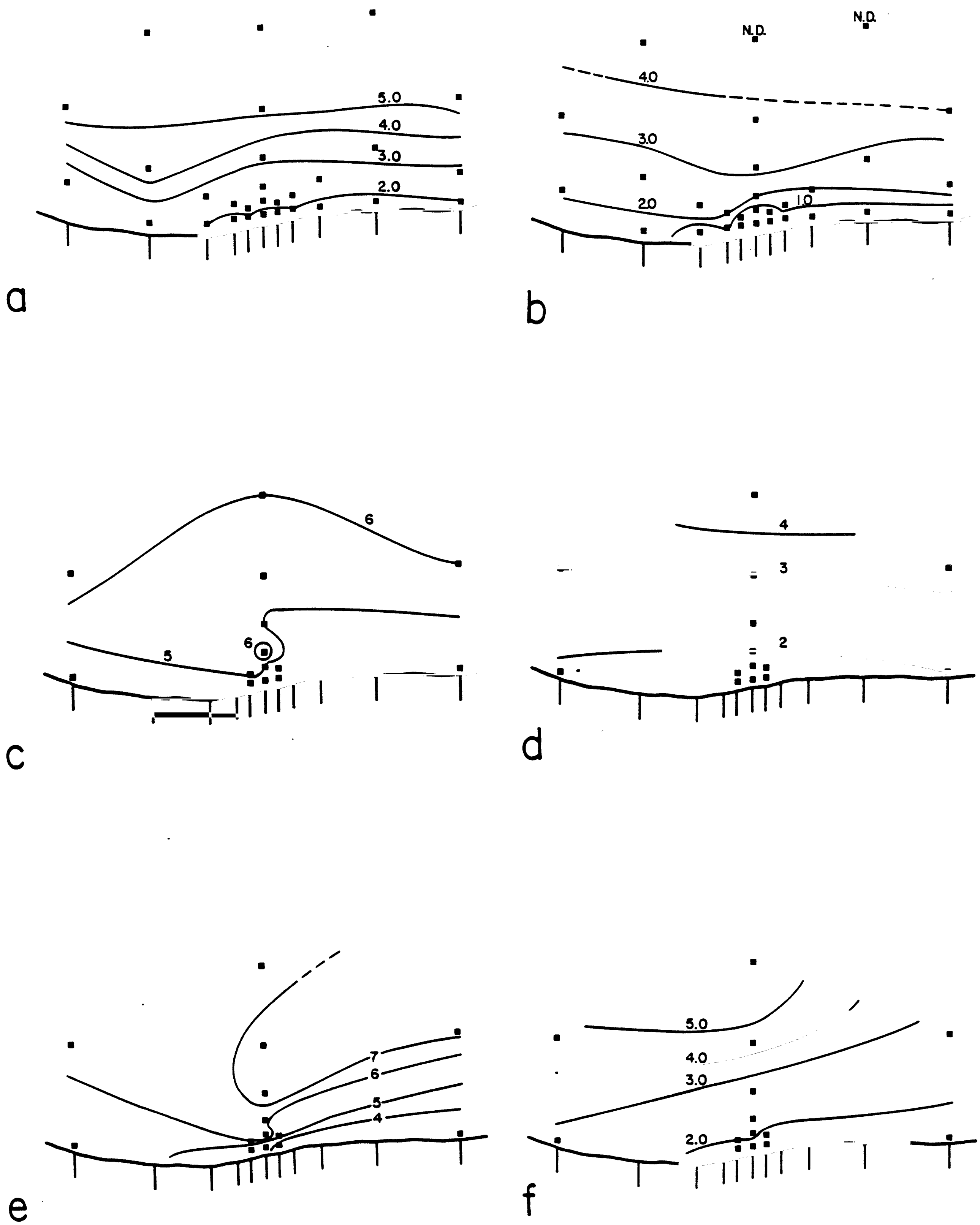

FIG. 3. Secchi disc depths in meters in a) 14 April 1977, b) 12 April 1978, c) 18 May 1977, d) 12 May 1978, e) 16 June 1977, f) 15 June 1978,

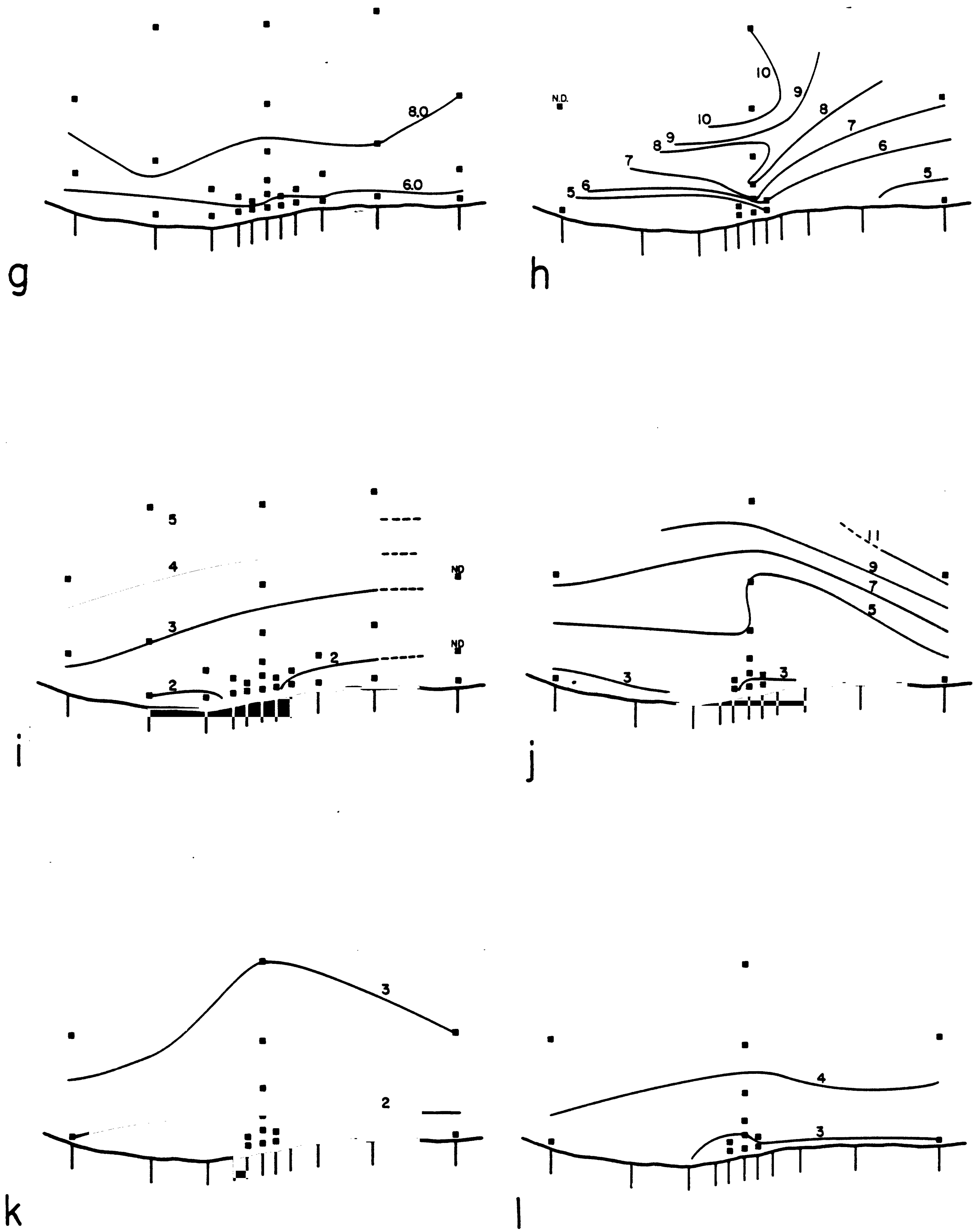

FIG. 3. Continued. g) 13 July 1977, h) 12 July 1978, i) 10 August 1977, j) 10 August 1978, k) 14 September 1977, l) 14 September 1978,

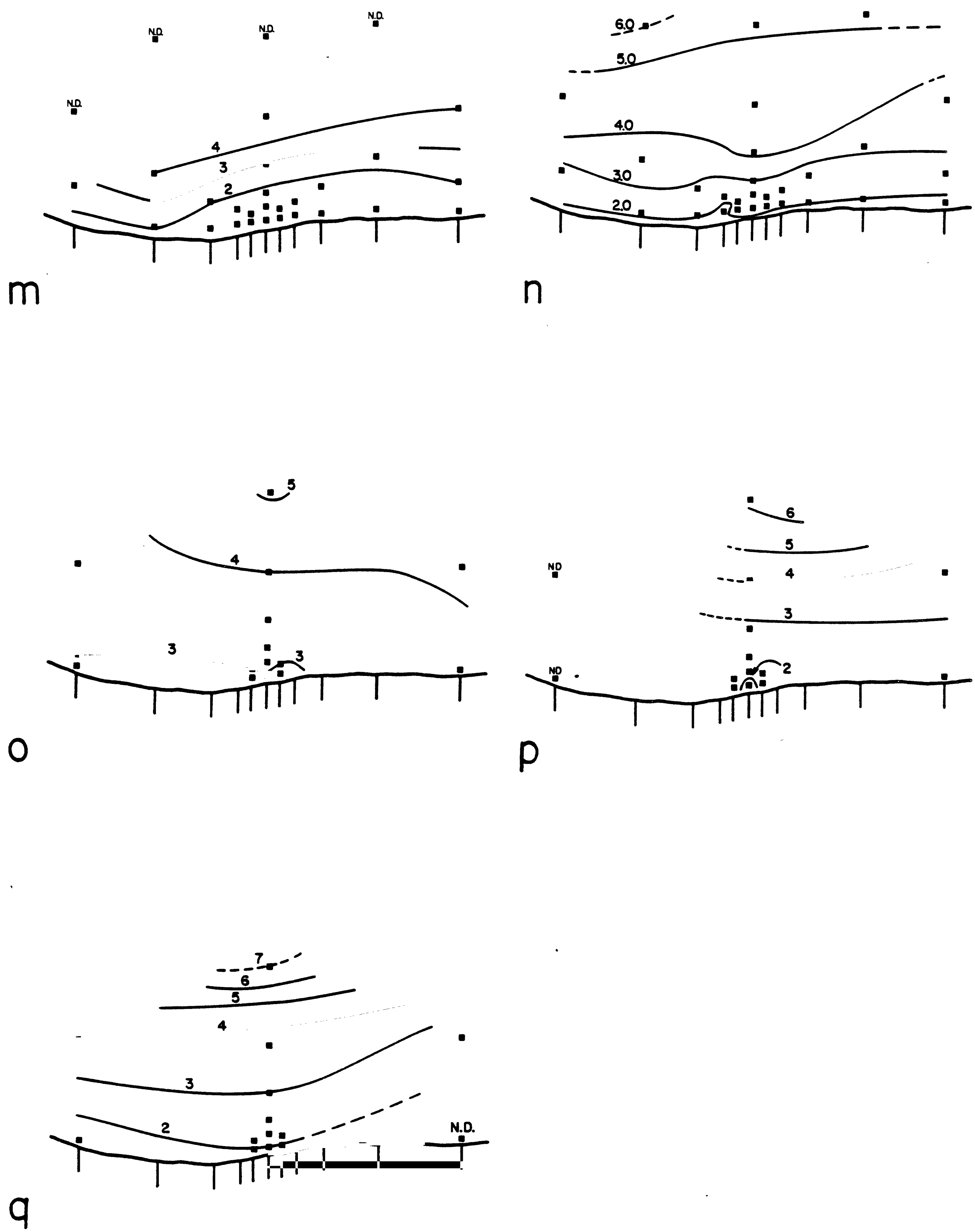

FIG. 3. Concluded. m) 14 October 1977, n) 11 October 1978, o) 9 November 1977, p) 16 November 1978, and q) 15 December 1977.

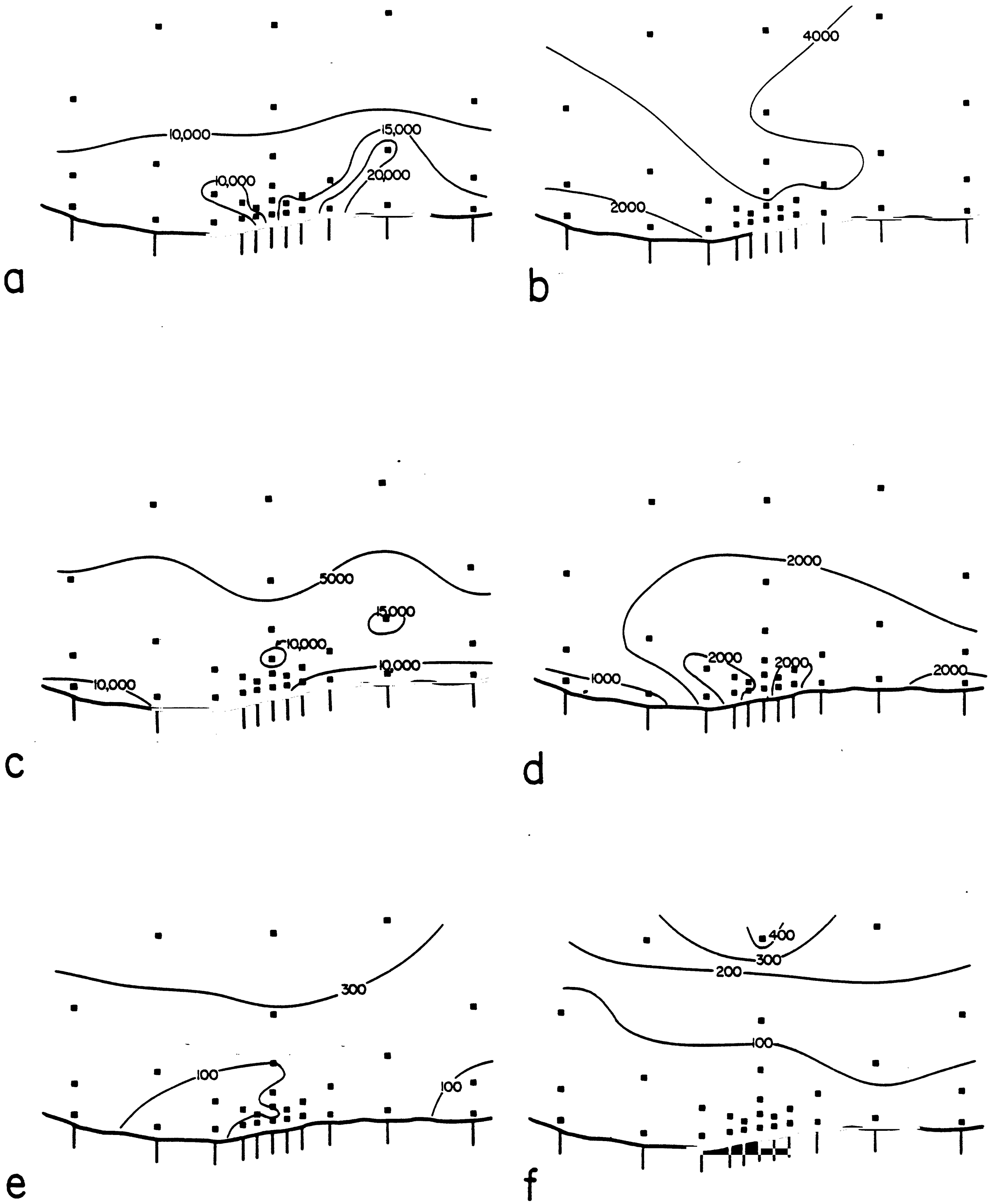

FIG. 4. Horizontal distributions (number/m^3) of total zooplankton and major zooplankton taxa collected on 14 April 1977 (left column) and 12 April 1978 (right column). a), b) total zooplankton; c), d) copepod nauplii; e), f) Cyclops spp. C1–C5;

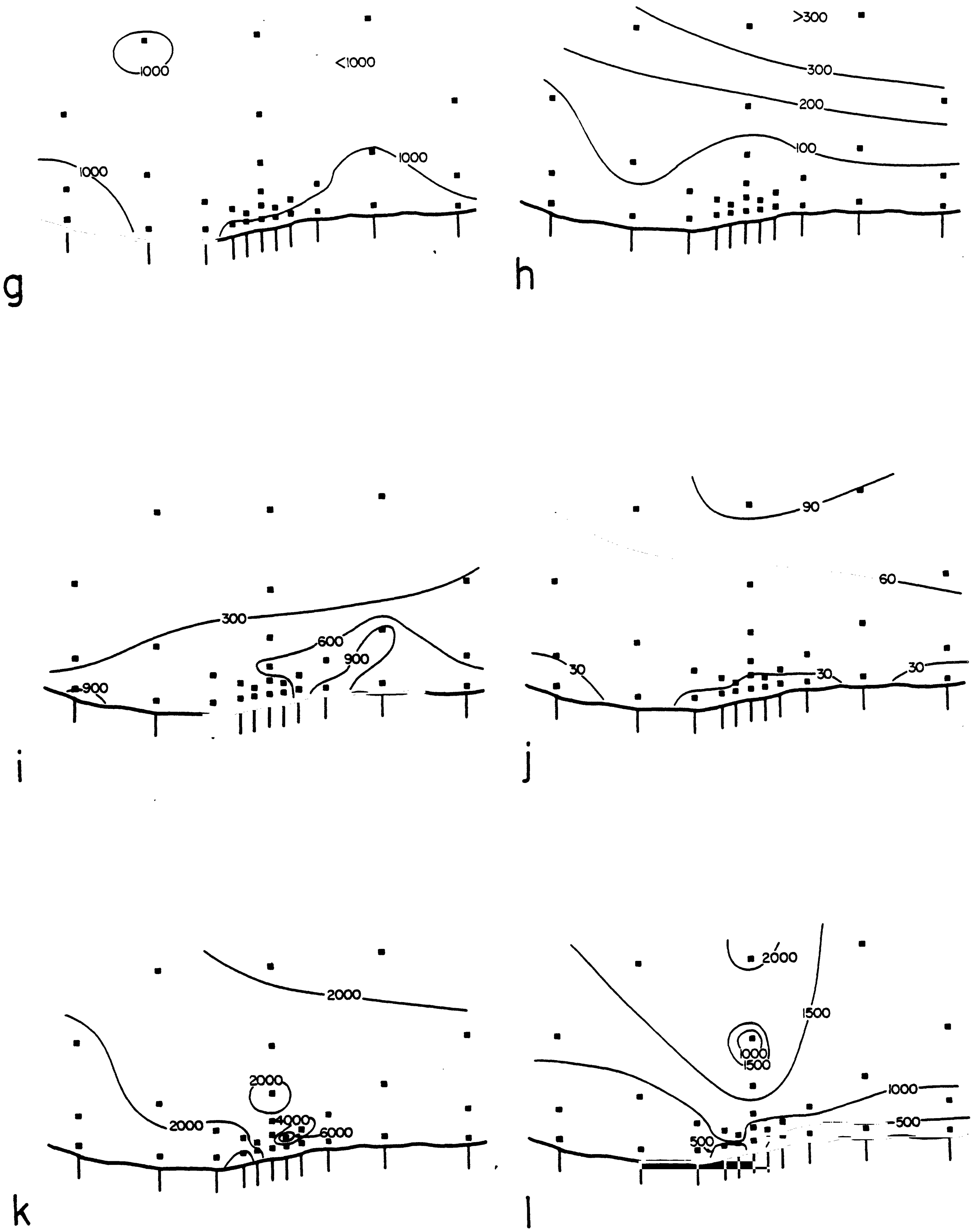

FIG. 4. Continued. g), h) Cyclops spp. C6; i), j) Diaptomus spp. C1–C5; k), l) Diaptomus spp. C6;

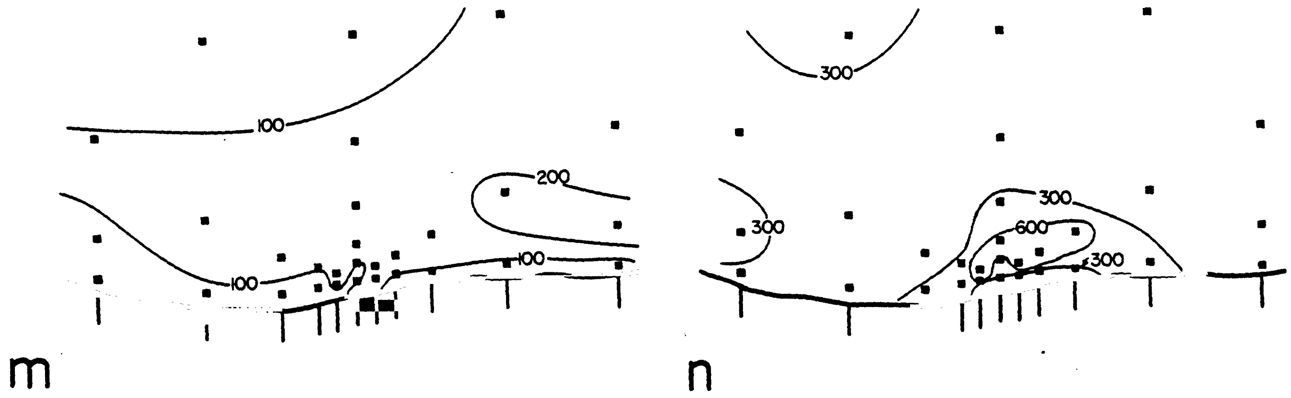

FIG. 4. Concluded. m), n) Limnocalanus macrurus C1-C6.

Cladocerans were rare at all stations with Bosmina longirostris (<120/m^3) the most common species.

Total zooplankton ranged in concentration from 7,000/m^3 to 15,000/m^3 with the highest concentrations occurring at stations closest to shore. Biomass ranged from 15 to 49 mg dry weight/m^3 (Fig. 5a), while station mean individual dry weight ranged from 1.4 to 3.2 μg.

14 April 1978

Surface water temperatures were lower than in 1977, ranging from 1.7 to 6.0°C, with the thermal bar 3 km offshore (Fig. 2b). The thermal plume was small and weakly defined. Secchi disc depths (Fig. 3b) ranged from 0.8 to 4.5 m; water color was pea green at shallow water stations and blue green in deeper waters.

Nauplii accounted for more than half of the zooplankton except at deep stations where this fraction was less. Adult Limnocalanus macrurus, Diaptomus sicilis, D. ashlandi, and D. minutus were of secondary abundance followed by Cyclops bicuspidatus thomasi and immature L. macrurus copepodites. As in the previous year, cladocerans were minor components of the April zooplankton assemblage. Zooplankton ranged in concentration from 1,600 to 5,200/m^3 (Fig. 4), while biomass ranged from 5 to 278 mg/m^3 (Fig. 5b), and station mean weights per individual ranged from 1.8 to 7.6 μg/individual. The largest fraction of station biomass was accounted for by D. sicilis, L. macrurus adults, and D. ashlandi adults.

Zooplankton were more abundant during the 1977 cruise than during the 1978 cruise, with the greatest differences associated with larger numbers of nauplii

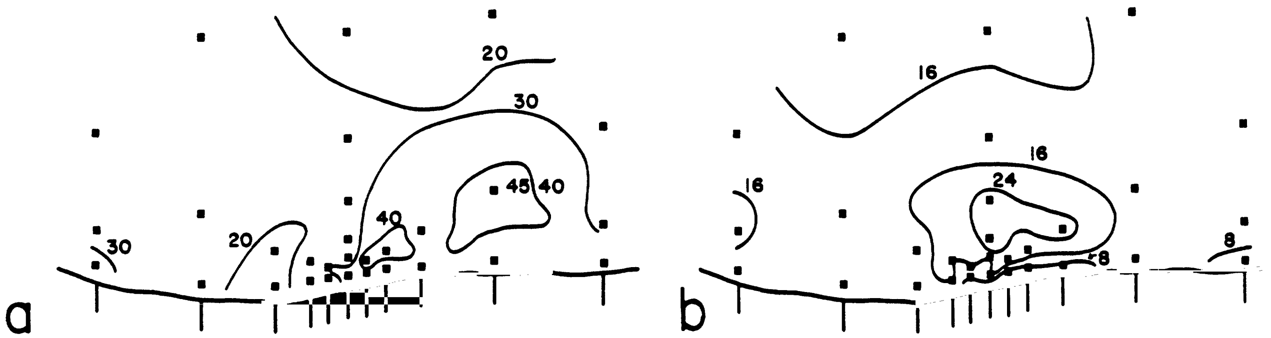

FIG. 5. The standing stock of zooplankton (mg dry weight/m^3) on a) 14 April 1977, b) 12 April 1978.

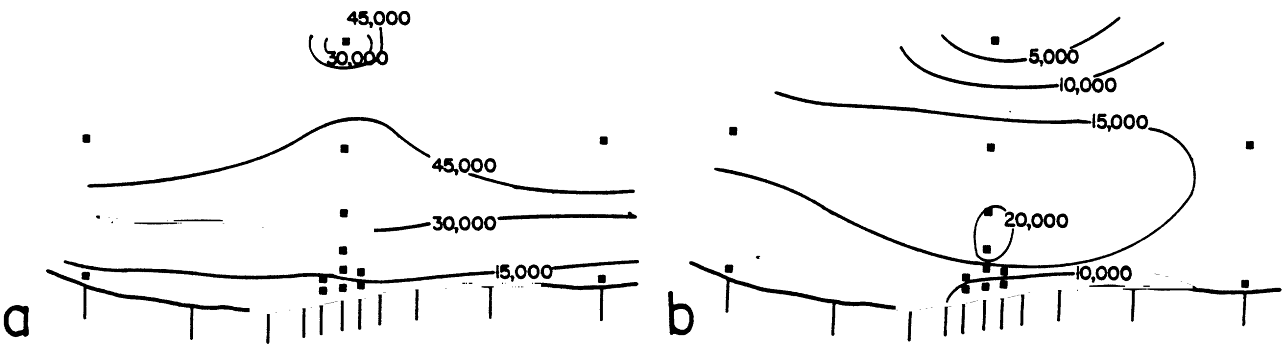

FIG. 6. The horizontal distribution (number/m^3) of total zooplankton collected on a) 18 May 1977, b) 12 May 1978.

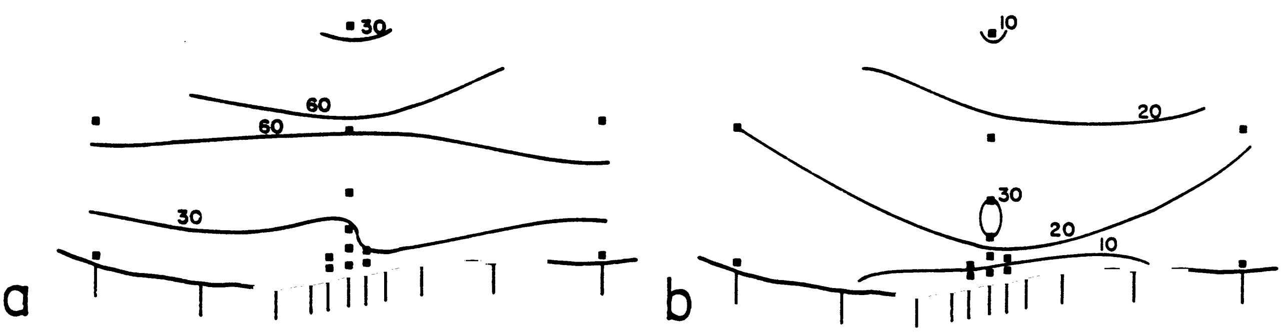

FIG. 7. The standing stock of zooplankton (mg dry weight/m^3) on a) 18 May 1977, b) 12 May 1978.

in 1977, although Cyclops bicuspidatus thomasi, D. ashlandi, and D. oregonensis adults and immature Diaptomus spp. copepodites also were more abundant in 1977. These differences in abundance probably were related to the fact that spring was warmer in April 1977 than in April 1978.

18 May 1977

Lake warming continued, with surface temperatures ranging from 9.5 to 17.0°C (Fig. 2c). The lake was thermally stratified at this time. The thermal plume was small and weakly defined. Secchi disc depths ranged from 4.2 to 6.8 m (Fig. 3c) and water color typically was green in shallow water stations and blue-green at deeper stations.

Zooplankton were numerically dominated by nauplii and by immature Cyclops spp. and Diaptomus spp. copepodites. Bosmina longirostris accounted for approximately 10% of the zooplankton over most of the survey grid. Diaptomus ashlandi, D. minutus, D. oregonensis, and D. sicilis were abundant with D. minutus the more common species over most of the survey grid. D. ashlandi was most common in deeper waters. Adult Cyclops bicuspidatus thomasi and immature Limnocalanus macrurus were minor constituents of the nearshore zooplankton assemblage but were of greater importance in deeper waters.

Total zooplankton concentrations ranged from 5,600 to 58,200/m^3 (Fig. 6a), while biomass ranged from 5 to 83 mg/m^3 (Fig. 7a), and mean individual weights ranged from 0.9 to 1.5 μg/individual. Nauplii, immature Cyclops, and Diaptomus spp. copepodites accounted for most of the biomass, while Bosmina longirostris was important inshore and L. macrurus offshore.

12 May 1978

Lake heating was less intense in May 1977, with surface water temperatures (Fig. 2d) ranging from 4.4 to 11.5°C on May 12. The lake had not thermally stratified at the time of the cruise. The thermal plume was small and weakly defined. Secchi disc depths ranged from 1.4 to 4.8 m (Fig. 3d) and water color was green.

Nauplii accounted for 40 to 70% of the zooplankton. This was about half the percentage which was observed during the May 1977 cruise. Immature *Cyclops* spp. and *Diaptomus* spp. copepodites were of secondary abundance. Among the adult diaptomids, *D. ashlandi* and *D. sicilis* were the numerically dominant forms, in contrast to May 1977 when *D. minutus* was dominant. Immature *Limnocalanus macrurus* accounted for several percent of the deepwater zooplankton.

Cladocerans were exceedingly rare. *Daphnia parvula*, a small cladoceran commonly associated with ponds and small lakes, was observed for the first time at a few stations (DC-2, DC-3, DC-4, NDC .5-2, and NDC 7-5). Abundances were less than $20/m^3$.

Zooplankton ranged in abundance from 9,000 to $20{,}500/m^3$ (Fig. 6b) and in biomass from 7 to 30 mg/m^3 (Fig. 7b). Station individual dry weight ranged from 0.8 to 1.9 μg. Nauplii and immature *Cyclops* and *Diaptomus* spp. copepodites accounted for a significant fraction of the nearshore biomass while *Limnocalanus macrurus* copepodites, adult *D. ashlandi*, *D. sicilis*, and *Cyclops bicuspidatus thomasi* accounted for a large fraction of the deep water zooplankton biomass.

Zooplankton tended to be more abundant during the May 1977 cruise than in May 1978, with the greatest differences associated with larger numbers of

immature Cyclops and Diaptomus spp. copepodites and Bosmina longirostris. Conversely, D. ashlandi and D. sicilis tended to be somewhat less abundant during the warmer May 1977 cruise.

16 June 1977

An upwelling occurred during the 16 June 1977 cruise with surface temperatures ranging from 13.0 to 20.5°C. The major center of upwelling was in the northern half of the survey area. The thermal plume was small (Fig. 2e) and weakly defined. Secchi disc depths (Fig. 3e) ranged from 3.0 to 7.5 m. Water color was blue-green.

Zooplankton were numerically dominated by Bosmina longirostris at most stations except at SDC 7-1, SDC .5-1, and NDC .5-1 where numbers and percent composition were low. Nauplii and immature Cyclops spp. and Diaptomus spp. copepodites were of secondary abundance. Cyclops bicuspidatus thomasi was the dominant adult cyclopoid. Diaptomus ashlandi dominated the adult diaptomid population in the cooler waters of the survey area while D. minutus dominated in warmer waters. Other cladocerans included Daphnia retrocurva, Eubosmina coregoni, and Polyphemus pediculus which were abundant at some stations. The rotifer Asplanchna spp. was relatively rare although it accounted for a few percentage of the zooplankton at NDC .5-1, NDC .5-2, and NDC 7-1, 37% at SDC .5-1 and 80% at SDC 7-1. Polyphemus pediculus also was abundant at these stations. These high abundances at station SDC 7-1 probably were related to the fact that water at this station was least affected by the upwelling as evidenced by the higher temperatures.

Zooplankton varied in density from 9,700/m^3 to 105,000/m^3 (Fig. 8a) while biomass ranged from 6 to 77 mg/m^3 (Fig. 9a). Lowest standing stocks of zooplankton were associated with station SDC .5-1; the reason for this is not known. Biomass ranged from 0.6 to 1.0 μg/individual, reflecting the dominance of zooplankton by the smaller *Bosmina longirostris* and immature *Cyclops* spp. and *Diaptomus* spp. copepodites. Immature *Cyclops* spp. copepodites were lighter in June (0.7 μg/individual) than in May (1.3 μg/individual) and may have been young from a second reproductive period. Immature *Diaptomus* spp. copepodites weighed approximately the same in May (1.4 μg/individual) and in June (1.6 μg/individual).

15 June 1978

The 15 June 1978 cruise also was conducted during an upwelling with surface temperatures ranging from 7.5 to 16.0 °C (Fig. 2f). These temperatures were lower than during the 16 June 1977 cruise, possibly in association with the cooler spring and early summer in 1978. As in June 1977, the upwelling was centered north of the survey area. Secchi disc depths ranged from 1.4 to 5.8 m (Fig. 3f). Water color was green inshore and blue-green at offshore stations.

The nearshore zooplankton were dominated by *Asplanchna* spp., *Bosmina longirostris*, nauplii, and by immature *Cyclops* spp. and *Diaptomus* spp. copepodites. These latter taxa were relatively more abundant at deeper (>20 m) stations. Adult diaptomids generally were dominated by *D. minutus*. Abundance isopleths paralleled shore, with most taxa increasing in abundance from shallow stations to deep stations. Taxa which were more abundant in the shallower areas

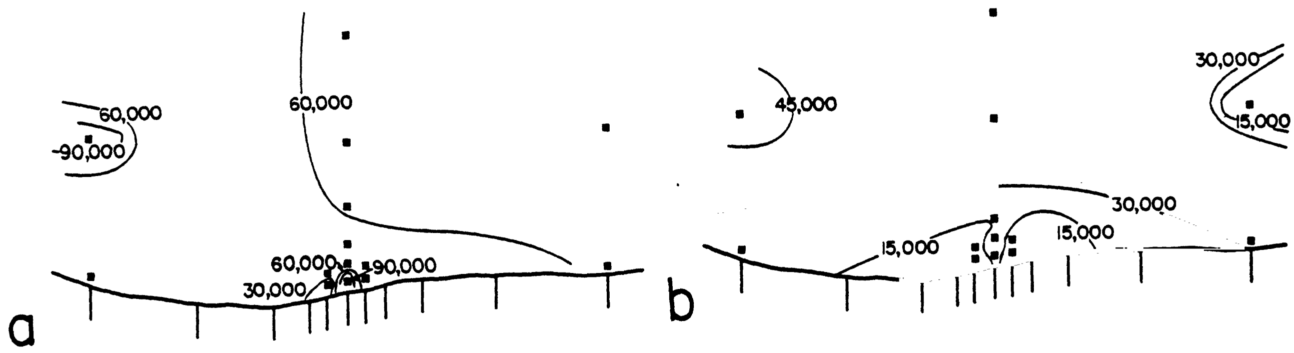

FIG. 8. The horizontal distribution of total zooplankton collected on a) 16 June 1977, b) 15 June 1978.

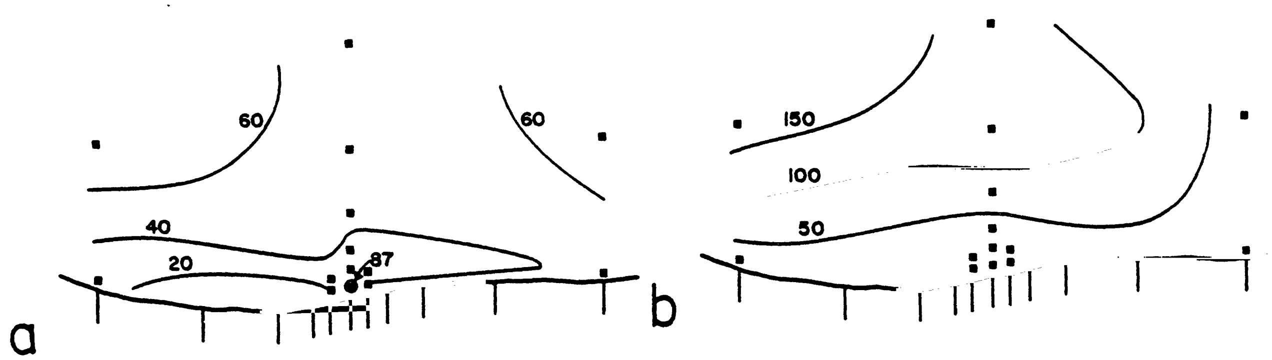

FIG. 9. The standing stock of zooplankton (mg dry weight/m^3) on a) 16 June, 1977, b) 15 June 1978.

of the survey grid were Eurytemora affinis, Bosmina longirostris, and Chydorus sphaericus.

Total zooplankton numbers varied from 7,200 to 48,900/m^3 (Fig. 8b) while biomass ranged from 10 to 180 mg/m^3 (Fig. 9b), and mean individual weights ranged from 1.1 to 4.6 μg/individual. Relatively heavy (4.4 μg/individual) immature Diaptomus, immature Cyclops spp. copepodites, and adults contributed a major fraction of the biomass at deeper stations.

13 July 1977

Surface temperatures ranged from 20.5 to 23.6 °C (Fig. 2g) and were slightly lower than during the 1975 and 1976 July cruises. The thermal plume was small and weakly defined. Secchi disc depths ranged from 4.0 to 9.5 m (Fig. 3g). Water color was green.

Bosmina longirostris was dominant in the inshore region while Cyclops spp. and Diaptomus spp. copepodites and Daphnia spp. increased in dominance with increasing station depth (Fig. 10). The numerically dominant cyclopoid was Cyclops bicuspidatus thomasi. Among the adult diaptomids, D. minutus dominated in shallow water while D. ashlandi increased in dominance with increasing station depth and accounted for a large fraction of the adult diaptomids in deeper waters. D. oregonensis and D. sicilis accounted for minor components of the adult population, increasing in dominance with station depth. Daphnia retrocurva was the dominant Daphnia species.

Total zooplankton ranged in concentration from 1,500/m^3 at shallow water stations to over 71,500/m^3 at deep water stations (Fig. 10). Biomass ranged from 2 to 124 mg/m^3 (Fig. 11a). Areas of low biomass occurred within the 10-m

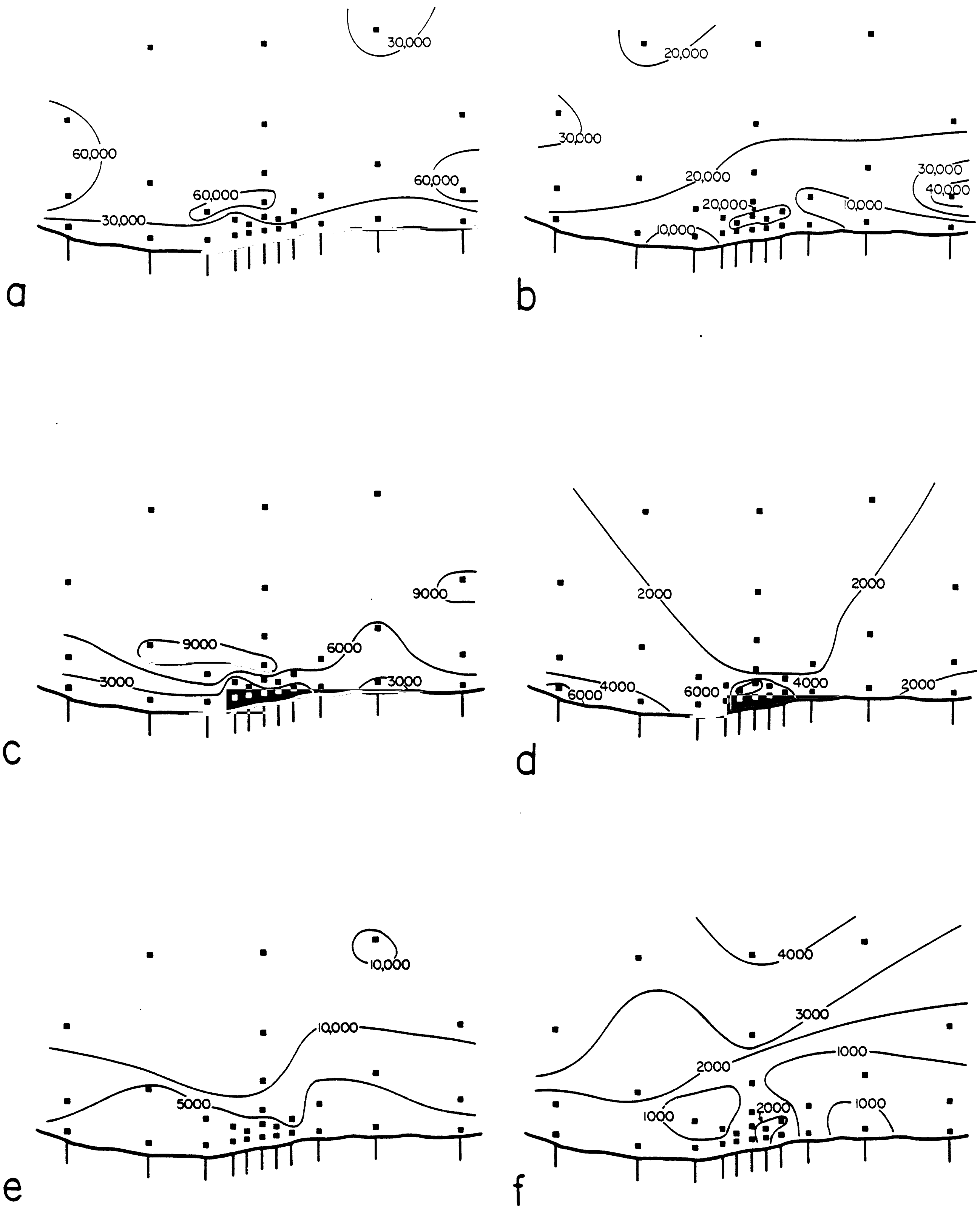

FIG. 10. Horizontal distributions (number/m^3) of total zooplankton and major taxa collected on 13 July 1977 (left column) and 12 July 1978 (right column). a), b) total zooplankton; c), d) copepod nauplii; e), f) Cyclops spp. C1-C5;

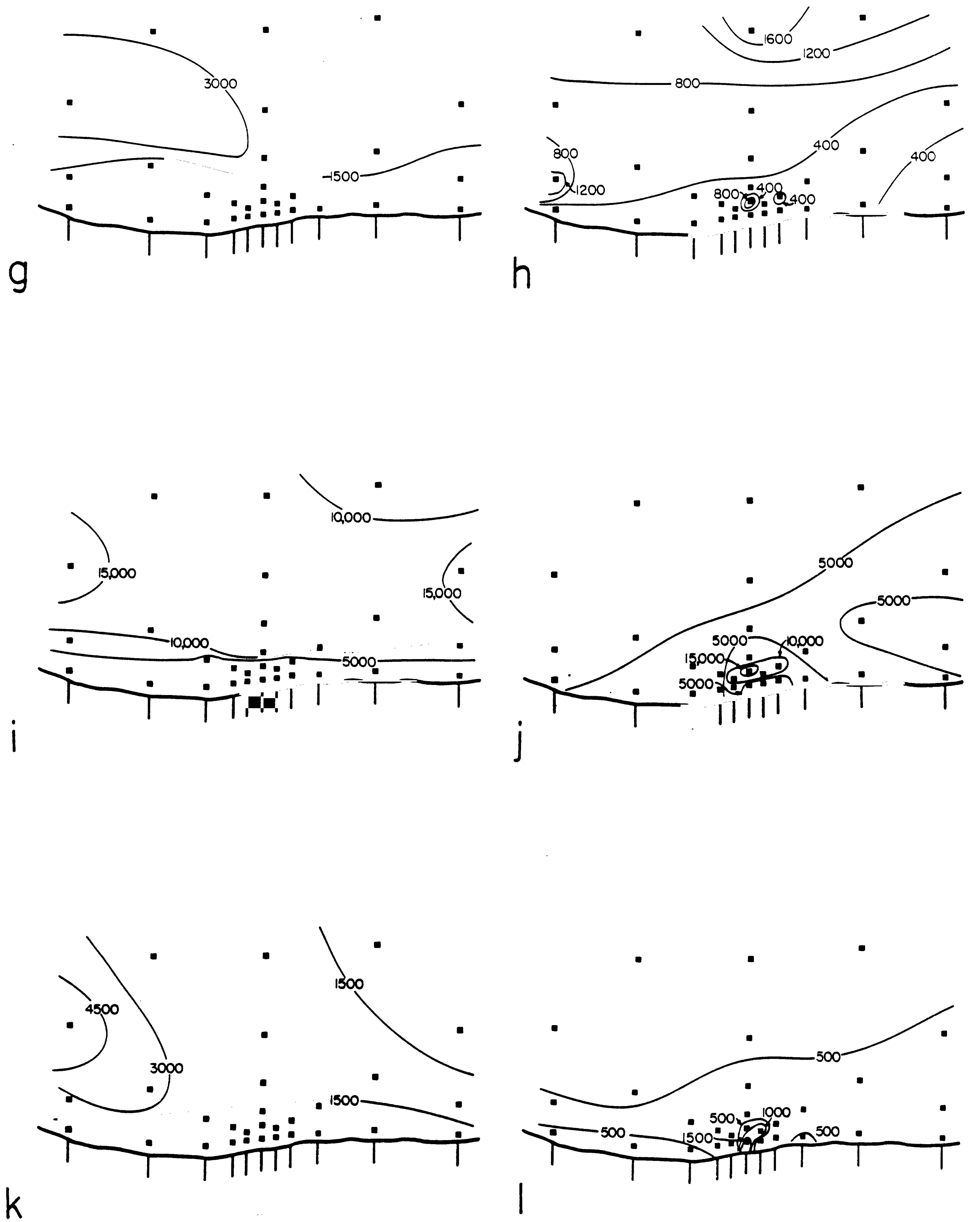

FIG. 10. Continued. g), h) Cyclops spp. C6; i), j) Diaptomus spp. C1-C5; k), l) Diaptomus spp. C6;

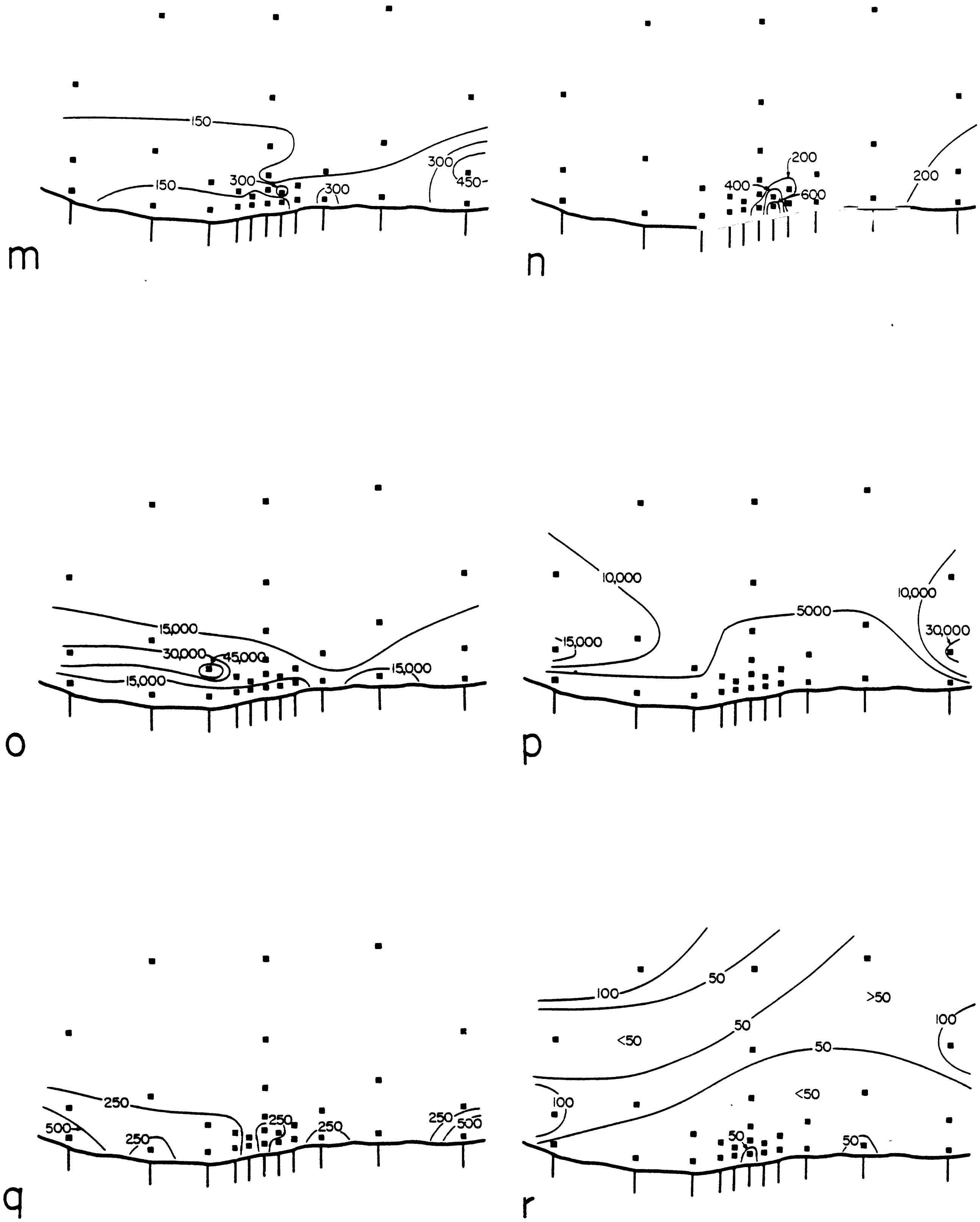

FIG. 10. Concluded. m), n) Eurytemora affinis C1–C6; o), p) Bosmina longirostris; q), r) Asplanchna spp.

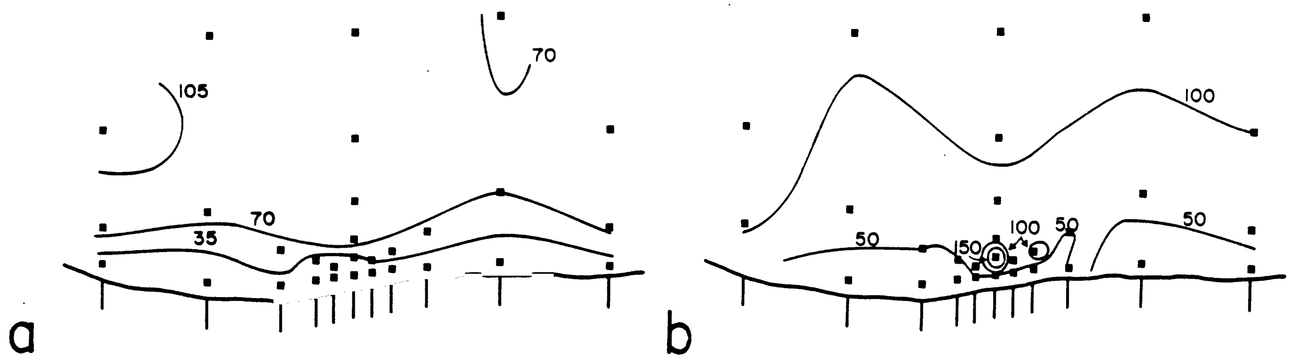

FIG. 11. The standing stock of zooplankton (mg dry weight/m^3) on a) 13 July 1977, b) 12 July 1978.

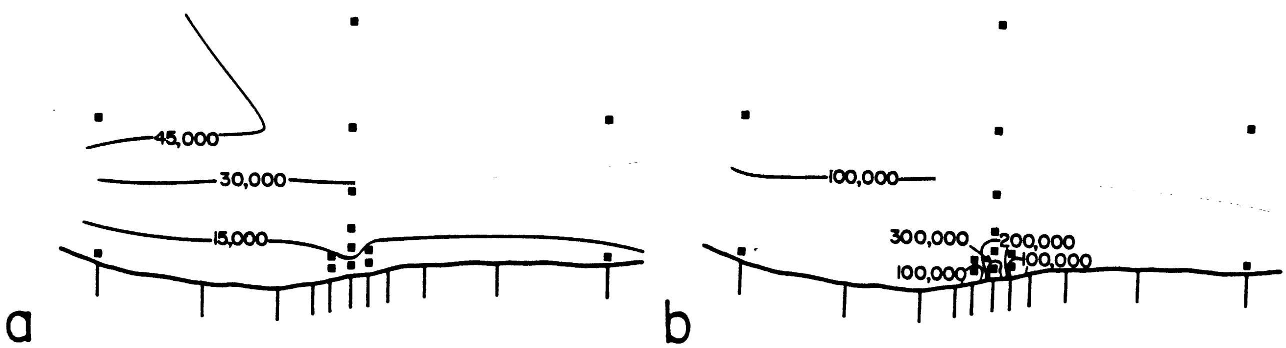

FIG. 12. The horizontal distribution of total zooplankton (number/m^3) collected on a) 10 August 1977, b) 10 August 1978.

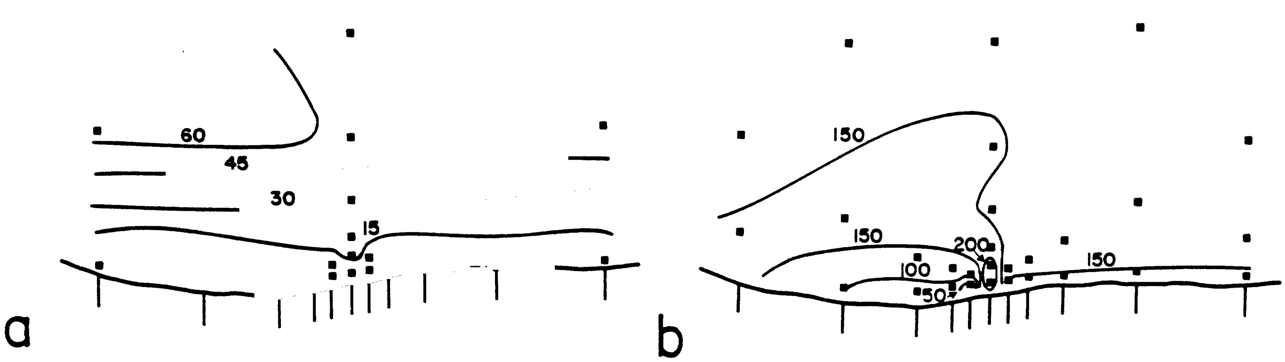

FIG. 13. The standing stock of zooplankton (mg dry weight/m^3) on a) 10 August 1977, b) 10 August 1978.

depth contour. Station mean weights per individual ranged from 0.9 μg in shallow waters to over 2.4 μg in deep waters. Nauplii, immature *Cyclops* spp. and *Diaptomus* spp. copepodites, and *Bosmina longirostris* were major components of the shallow-water biomass while the major components of the deepwater biomass included *Daphnia retrocurva*, *D. galeata mendotae*, *Diaptomus minutus*, and *D. ashlandi*.

12 July 1978

An upwelling occurred during the 12 July 1978 cruise, with surface water temperatures ranging from 7.1 to 18.9°C (Fig. 2h). The thermal plume was small and ill-defined. Secchi disc depths ranged from 1.8 to 5.5 m (Fig. 3h). Water color was green inshore and blue-green offshore.

Zooplankton were numerically dominated by nauplii and immature *Cyclops* and *Diaptomus* spp. copepodites, while *Bosmina longirostris* was a significant component of the zooplankton in the warmer offshore waters (Fig. 10). The dominant diaptomid adult species was *D. ashlandi* followed by *D. sicilis*. The latter species inhabits the hypolimnion during the summer, and its presence in the nearshore area is a further indication of an upwelling event. Similarly, the hypolimnetic species *Limnocalanus macrurus* was collected at shallow water stations in association with the upwelling.

Total zooplankton varied in density from 5,300/m^3 to a maximum of 45,600/m^3 (Fig. 10). Biomass ranged from 7 to 156 mg/m^3 (Fig. 11b). Station individual biomass ranged from 1.1 to 6.2 μg. Immature *Diaptomus* spp. copepodites and *Limnocalanus macrurus* accounted for the largest biomass fraction at most stations.

10 August 1977

Surface water temperatures ranged from 21.7 to 23.5°C (Fig. 2i). The thermal plume was small and weakly defined. Secchi disc depths ranged from 3.6 to >12 m (Fig. 3i). Water color was blue-green.

The numerically dominant taxa included nauplii and immature *Cyclops* and *Diaptomus* spp. copepodites, while *Bosmina longirostris* and *Daphnia retrocurva* were of secondary abundance at some shallow water stations. *Diaptomus minutus* was the major diaptomid species followed by *D. ashlandi*.

Zooplankton abundances ranged from 3,800/m^3 to 55,900/m^3 (Fig. 12a) with zooplankton tending to be least abundant closer to shore. Biomass ranged from 3 to 76 mg/m^3 (Fig. 13a) and from 0.8 μg/individual at shallow water stations to 1.7 μg/individual at deepwater stations. Immature *Diaptomus* spp. accounted for the major fraction of zooplankton biomass at most stations followed by *Daphnia retrocurva*.

10 August 1978

Surface water temperatures ranged from 21.0 to 23.0°C (Fig. 2j). The thermal plume was small and weakly defined. Secchi disc depths ranged from 2.7 to 11.8 m (Fig. 3j) and water color was green inshore and blue-green offshore.

Bosmina longirostris dominated the zooplankton, followed by nauplii and immature *Cyclops* spp. and *Diaptomus* spp. copepodites. *Diaptomus ashlandi* was the numerically dominant adult diaptomid, followed by *D. minutus*. *Asplanchna* spp. accounted for a numerically significant fraction of the zooplankton at some nearshore stations.

Zooplankton densities varied from 21,700/m^3 to 318,900/m^3 (Fig. 12b). High zooplankton densities were observed over the discharge jets and 0.8 km to the north. Bosmina longirostris densities varied from a high of 294,300/m^3 over the discharge jets to a low of 800/m^3 at the stations furthest from shore. Densities were highly variable in the vicinity of the discharge jets ranging from 9,000/m^3 0.8 km north of the plant to 27,300/m^3 0.8 km south of the plant.

Biomass ranged from 17 to 232 mg/m^3 (Fig. 13b) with the greatest variability occurring in the vicinity of the discharge jets. Individual station biomass varied from a low of 0.7 μg for stations which were numerically dominated by B. longirostris to a high of 3.1 μg at stations located offshore. Most of the station biomass was accounted for by Bosmina longirostris, although immature Diaptomus spp. copepodites, D. sicilis, Limnocalanus macrurus, and Daphnia retrocurva accounted for a significant fraction of the deepwater biomass.

14 September 1977

Lake cooling was evident by the time of the September cruise, with surface water temperatures ranging from 16.4 to 17.5°C (Fig. 2k). The lake was well-stratified at this time. The thermal plume was small and weakly defined. Secchi disc depths ranged from 0.9 to 3.8 m (Fig. 3k) and water color was green.

Zooplankton were numerically dominated by nauplii, immature Diaptomus spp. and Cyclops spp. copepodites, and Bosmina longirostris. The dominant diaptomid adult species was D. ashlandi, while Daphnia retrocurva was the numerically dominant Daphnia species. Senecella calanoides, a rare hypolimnetic copepod, was observed at DC-3.

Zooplankton densities ranged from 14,500 to 79,100/m^3 (Fig. 14a), with the highest densities observed at the northern half of the survey grid. Biomass ranged from 21 to 60 mg/m^3 (Fig. 15a) and from 0.8 to 2.4 μg/individual.

14 September 1978

Surface water temperature ranged from 17.7 to 20.6°C (Fig. 2-1). There was slight evidence of an upwelling with isotherms running diagonal to shore. As in previous months, the thermal plume was small and weakly defined. Secchi disc depths ranged from 2.8 to 4.9 m (Fig. 3-1). Water color was gray-green inshore and blue-green offshore.

Zooplankton were numerically dominated by immature Cyclops spp. and Diaptomus spp. copepodites. Bosmina longirostris and Daphnia retrocurva were abundant at some nearshore stations. Diaptomus minutus was the numerically dominant adult diaptomid. Limnocalanus macrurus adults were observed in low numbers at deepwater stations.

Zooplankton varied in abundance from 13,500 to 35,800/m^3 (Fig. 14b), while biomass varied from 21 to 73 mg/m^3 (Fig. 15b). Individual station biomass varied from 1.3 to 5.5 μg/individual. Limnocalanus macrurus, while rare, accounted for more than half the biomass at deeper offshore stations.

14 October 1977

The epilimnion had mixed down to depths of 40 m by the time of the 14 October 1977 cruise. Surface temperatures ranged from 12.0 to 13.0°C (Fig. 2m). Secchi disc depths ranged from 1.4 to 4.6 m (Fig. 3m). Water color was green.

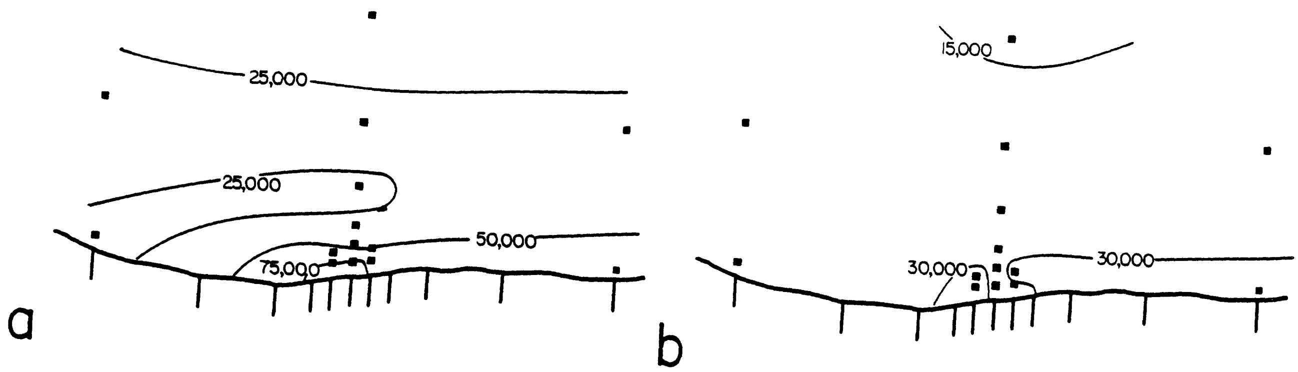

FIG. 14. The horizontal distribution of total zooplankton (number/m^3) collected on a) 14 September 1977, b) 14 September 1978.

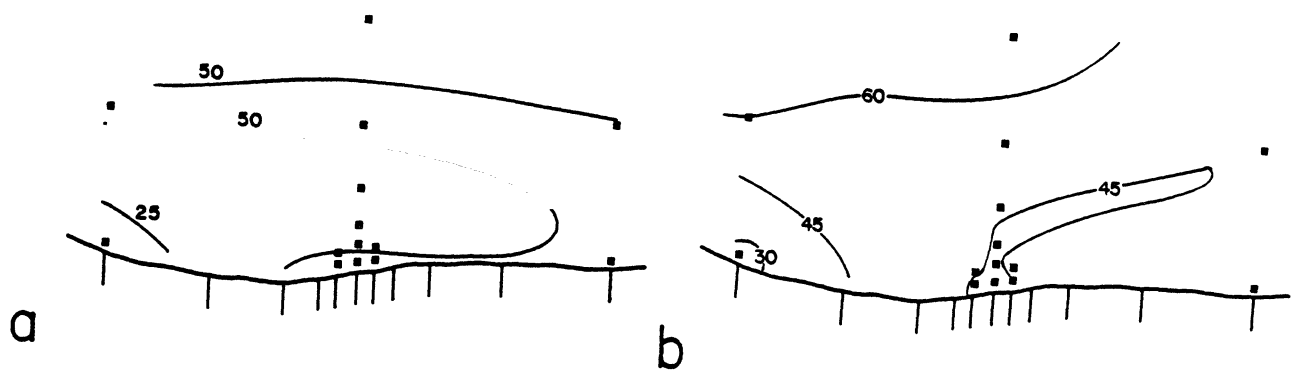

FIG. 15. The standing stock of zooplankton (mg dry weight/m^3) on a) 14 September 1977, b) 14 September 1978.

Zooplankton were numerically dominated by nauplii, immature *Cyclops* spp. and *Diaptomus* spp. copepodites, and *Bosmina longirostris* (Fig. 16).

Total abundances ranged from 13,400 to 63,500/m^3 (Fig. 16) and biomass from 15 to 112 mg/m^3 (Fig. 17a). Mean station biomass ranged from 0.7 to 2.1 µg/individual. Immature *Cyclops* spp. and *Diaptomus* spp., and *Bosmina longirostris*, were the major components of station biomass.

11 October 1978

The lake was thermally stratified during the 11 October 1978 cruise. Surface temperatures ranged from 12.8 to 15.9°C (Fig. 2n). Secchi disc depths ranged from 1.5 to 6.0 m (Fig. 3n). Color was gray-green at shallow stations and blue-green at deeper stations.

Zooplankton were numerically dominated by immature *Cyclops* and *Diaptomus* spp. copepodites and by *Daphnia galeata mendotae* (Fig. 16). *Bosmina longirostris* was numerically important at some shallow water stations.

Daphnia pulex, a pond cladoceran which is found in eutrophic Great Lakes areas such as Green Bay, was found for the first time in the survey area. This species occurred at low numbers at several stations and accounted for less than 1% of the zooplankton. *Mesocyclops edax*, a cyclopoid copepod which was common in Lake Michigan prior to the alewife population peak but has occurred in reduced numbers since the mid 1960s, occurred at all stations in densities which ranged from 24/m^3 to 481/m^3 and averaged 175/m^3.

Zooplankton densities varied from 9,500 to 52,200/m^3 (Fig. 16) and biomass ranged from 15 to 112 mg/m^3 (Fig. 17b). Individual station biomass ranged from

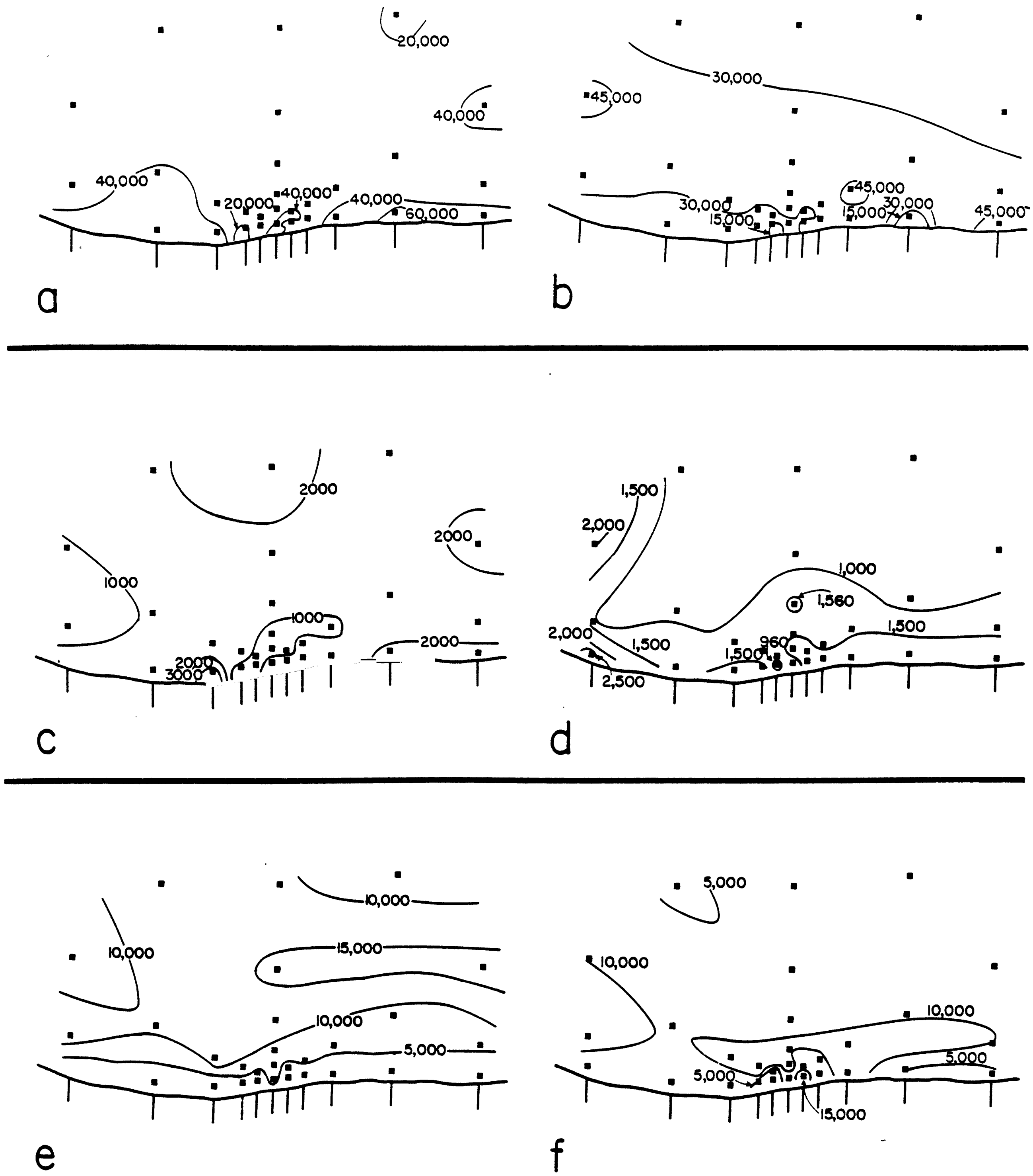

FIG. 16. Horizontal distribution (number/m^3) of total zooplankton and major taxa collected on 14 October 1977 (left column) and 11 October 1978 (right column). a), b) total zooplankton; c), d) copepod nauplii; e), f) Cyclops spp. C1-C5;

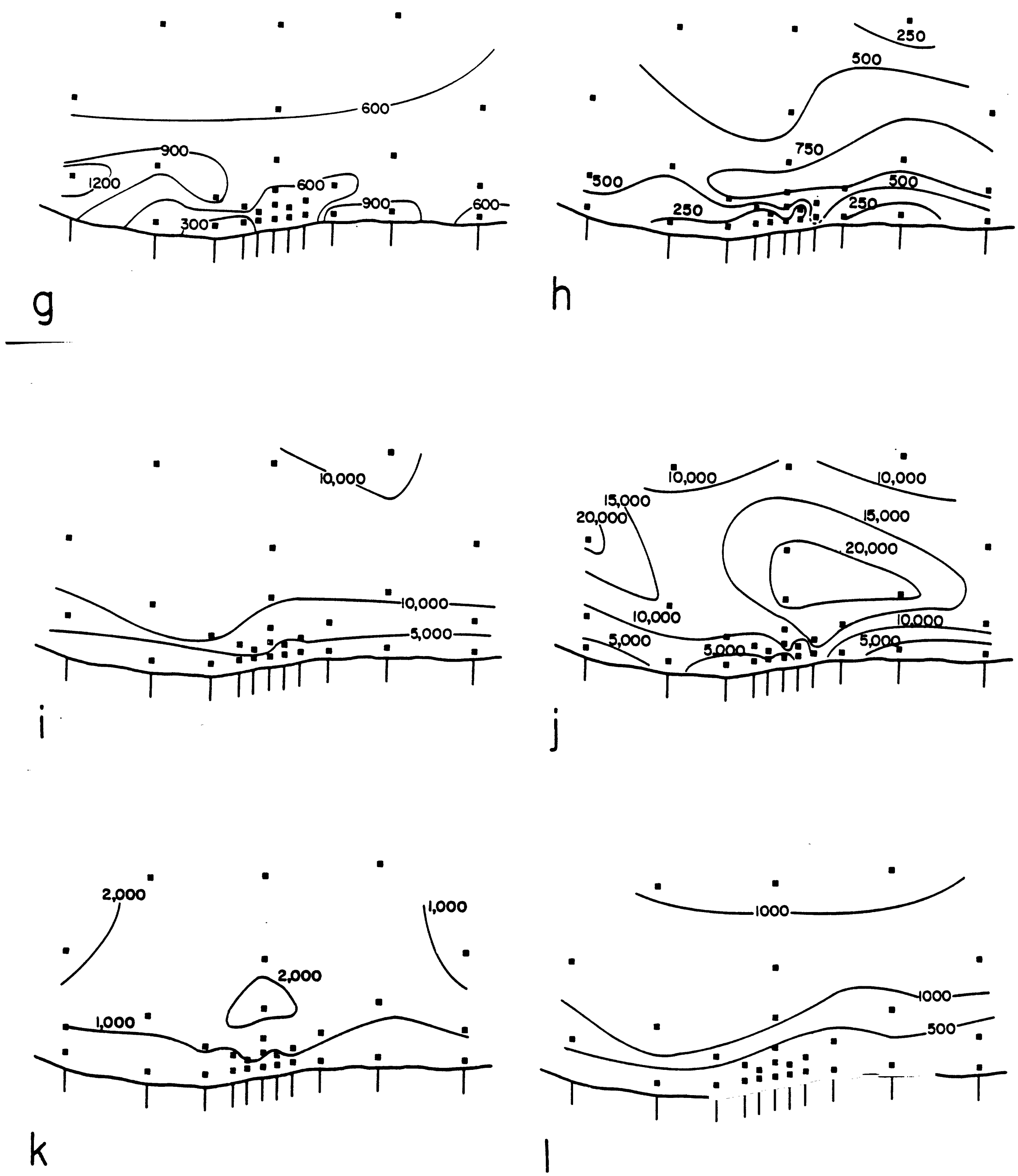

FIG. 16. Continued. g), h) Cyclops spp. C6; i), j) Diaptomus spp. C1-C5; k), l) Diaptomus spp. C6;

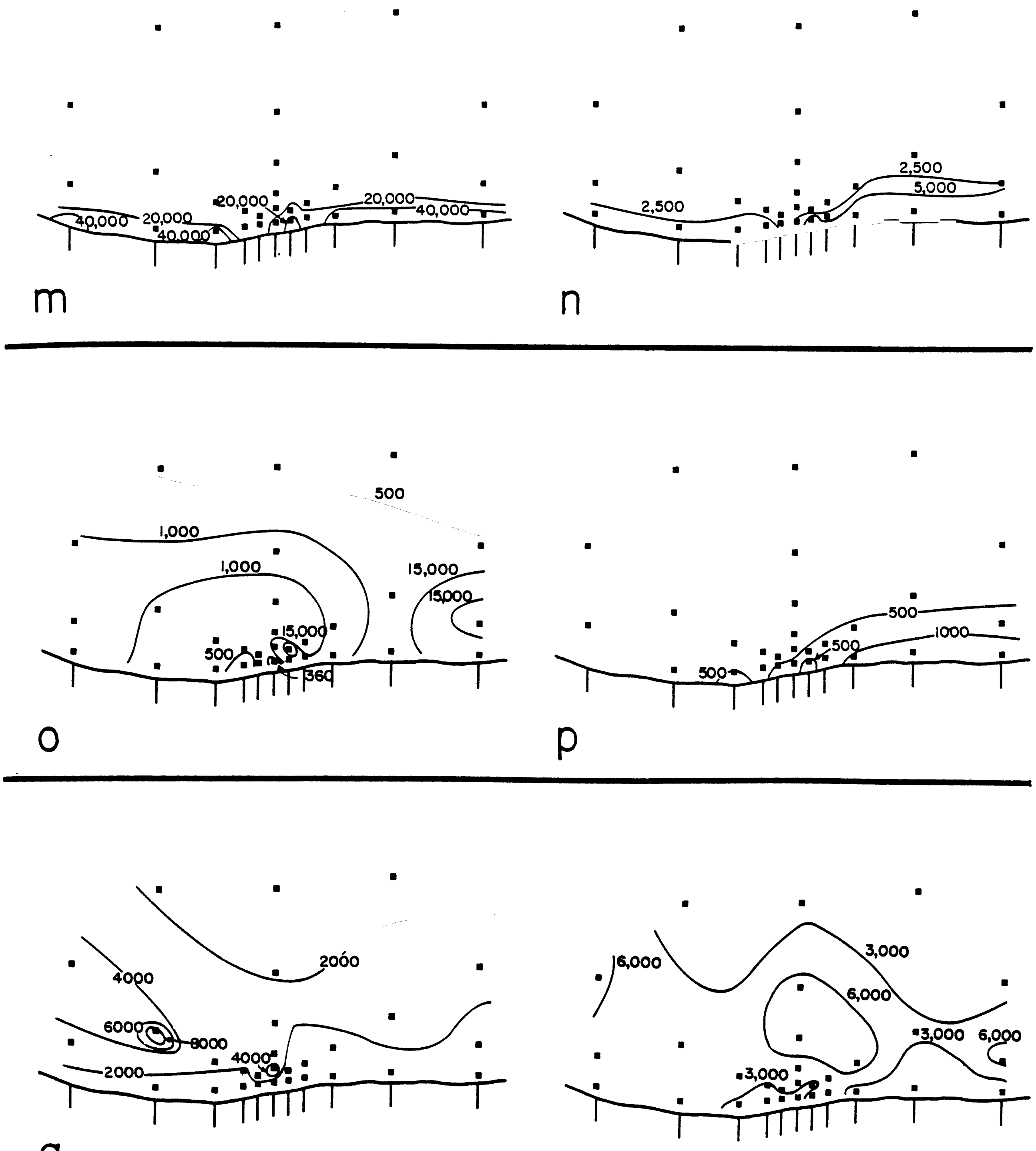

FIG. 16. Concluded. m), n) Bosmina longirostris; o), p) Eubosmina coregoni; q), r) Daphnia spp.

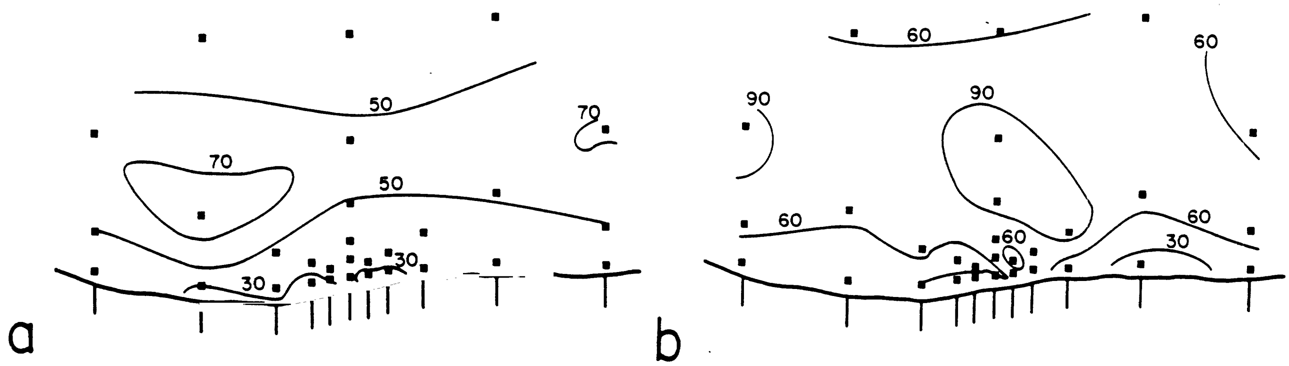

FIG. 17. The standing stock of zooplankton (mg dry weight/m^3) on a) 14 October 1977, b) 11 October 1978.

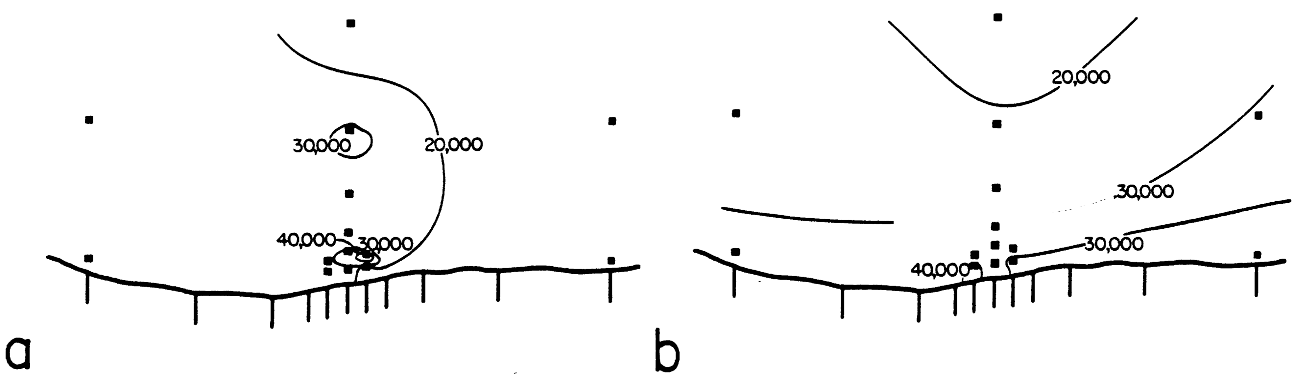

FIG. 18. The horizontal distribution of total zooplankton (number/m^3) collected on a) 9 November 1977, b) 16 November 1978.

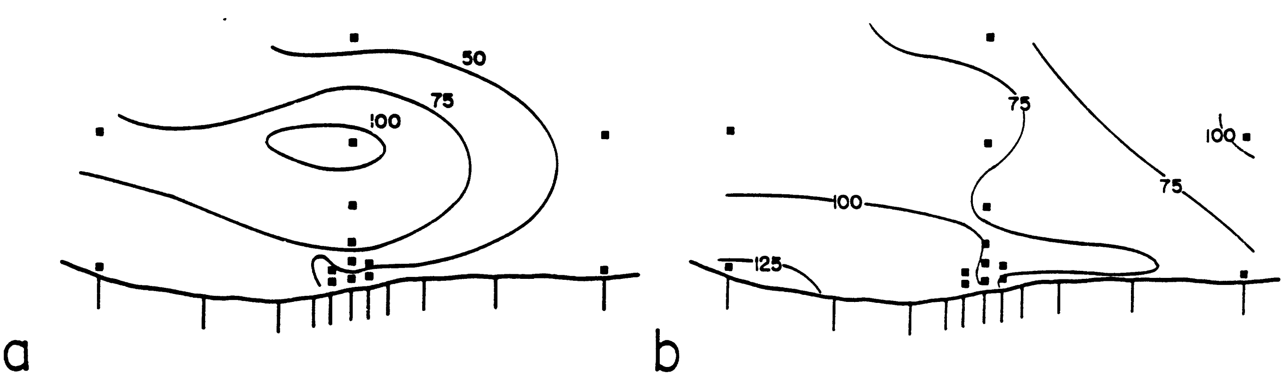

FIG. 19. The standing stock of zooplankton (mg dry weight/m^3) on a) 9 November 1977, b) 16 November 1978.

0.8 to 3.8 μg. Immature *Diaptomus* spp. and *Daphnia galeata mendotae* accounted for the most significant fraction of the biomass at most stations.

16 November 1977

Surface water temperature varied from 11.0 to 11.8°C (Fig. 2o), only slightly cooler than the previous month. In addition, the epilimnion was thinner, reaching depths of 25 m versus 40 m in October. The thermal plume was small and weakly defined. Secchi disc depths ranged from 2.5 to 5.0 m (Fig. 3o). Color was milky green.

Zooplankton were dominated by nauplii and by immature *Cyclops* spp. and *Diaptomus* spp. copepodites. Among adult diaptomids, *D. ashlandi*, *D. oregonensis*, and *D. sicilis* were the major species. Cladocerans generally accounted for a smaller fraction of the zooplankton with *Bosmina longirostris* the most common species. However, *Eubosmina coregoni*, *Daphnia galeata mendotae*, and the rotifer *Asplanchna* spp. were numerous at some stations.

Densities ranged from 11,300 to 40,800/m^3 (Fig. 18a), while biomass ranged from 25 to 111 mg/m^3 (Fig. 19a). Station biomass averaged 1.5 to 3.6 μg/individual, reflecting the dominance of larger individuals over the previous month's sampling.

16 November 1978

Surface temperatures varied from 9.0 to 10.0°C (Fig. 2p). Stratification was absent. Secchi disc depths ranged from 2.0 to 6.1 m (Fig. 3p) and water was gray-green.

Zooplankton were numerically dominated by immature _Cyclops_ spp. and _Diaptomus_ sp. copepodites and _Eubosmina coregoni_. All four species of adult diaptomids (_D. ashlandi_, _D. minutus_, _D. oregonensis_, and _D. sicilis_) accounted for a significant fraction of the zooplankton at most stations.

Zooplankton densities ranged from 17,500 to 40,900/m^3 (Fig. 18b), while biomass ranged from 67 to 123 mg/m^3 (Fig. 19b). Individual biomass ranged from 2.7 to 4.6 μg/individual, again reflecting the increase in the dominance of larger zooplankton over the preceeding cruise.

Daphnia pulex, which was collected for the first time in the October 1978 cruise, was again observed at seven stations during the November 1978 cruise at densities of <50/m^3. _Mesocyclops edax_ occurred at most stations, as it had in October 1978, but in lesser numbers. Densities reached 350/m^3 at some stations and averaged 140/m^3.

15 December 1977

Surface temperatures ranged from 1 to 4°C (Fig. 2q), as a result of continued cooling from the November 1977 cruise. The thermal plume was small and weakly defined. Secchi disc depths ranged from 1.8 to >7 m (Fig. 3q). Water color was not noted.

Zooplankton were dominated by adult _Diaptomus ashlandi_ and immature _Cyclops_ spp. copepodites, followed by _Eubosmina coregoni_, _D. sicilis_, _D. oregonensis_, _D. minutus_ and, to a lesser extent, immature _Diaptomus_ spp. and nauplii. Densities ranged from 7,500 to 16,400/m^3 (Fig. 20), while biomass ranged from 25 to 60 mg/m^3 (Fig. 21). Individual station biomass averaged 3.2 to 5.8 μg/individual.

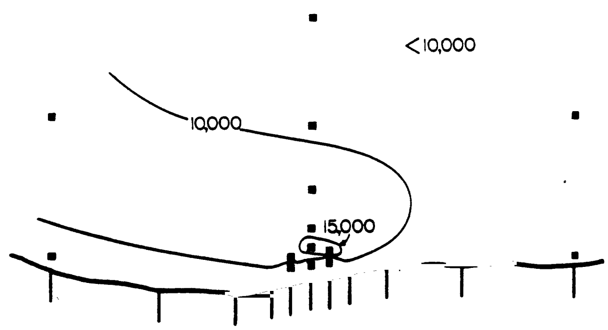

FIG. 20. The horizontal distribution of total zooplankton (number/m^3) collected on 15 December 1977.

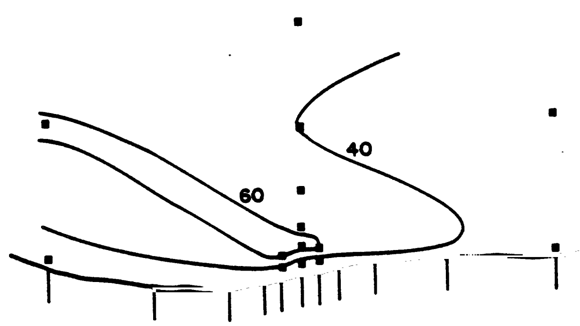

FIG. 21. The standing stock of zooplankton (mg dry weight/m^3) on 15 December 1977.

Principal Component Analysis of 1977 and 1978 Data

A total of seven analyses were performed utilizing the major survey data from the April, July, and October cruises for 1977 and 1978 and the December 1977 short survey data. In 1977 and 1978, the first principal component accounted for 42 to 75% of the total variance while the second principal component accounted for an additional 15 to 28% of the variance (Table 1). These values are similar to those reported for 1974, 1975, and 1976 data (Evans 1975, Evans *et al*. 1978).

Table 1. The percentage of total variance explained by principal components 1 (PC 1), 2 (PC 2) and the two components combined in analyses of major survey samples.

PC	April 1977	April 1978	July 1977	July 1978	October 1977	October 1978	December 1977
PC 1	42.2	75.1	69.0	47.1	68.9	64.4	66.9
PC 2	28.4	16.8	16.5	23.0	14.9	16.8	23.7
Sum	70.6	91.9	85.5	70.1	83.8	81.1	90.5

The first principal component (PC1) was highly correlated to station depth ($|r| > 0.6$) except in the April 1977 analysis ($|r| = 0.48$, Table 2). The strength of the correlation between PC1 and total zooplankton numbers varied considerably ($0.2 < |r| < 0.9$, Table 2). Previous analyses of the 1972-1976 data have also shown a strong relationship between PC1 and depth (Evans 1975, Evans *et al*. 1978, Evans *et al*. 1980).

Table 2. Correlations (r) between zooplankton (log #/m^3 + 1) taxa used in the analyses, station depth, total zooplankton and the first principal component.

Taxon	April 1977	April 1978	July 1977	July 1978	October 1977	October 1978	December 1977
Copepod nauplii	.48	.11	.83	-.31	.03	-.50	.20
Cyclopoid copepods C1-C5	.41	.98	.96	-.09	.80	.25	-.04
Cyclops spp. C6	.94	.99	.97	.64	.29	.58	.76
Tropocyclops prasinus m. C1-C6	--	--	--	--	.26	.05	.26
Diaptomus spp. C1-C5	.61	.92	.97	.31	.85	.82	-.17
Diaptomus spp. C6	.32	.79	.84	.17	.93	.86	.23
Epischura lacustris C1-C6	--	--	-.20	--	-.36	-.25	--
Eurytemora affinis C1-C6	--	--	-.31	-.43	-.95	-.92	--
Limnocalanus macrurus C1-C6	-.64	.09	--	.81	--	--	-.66
Bosmina longirostris	--	--	.34	.68	-.94	-.94	.90
Daphnia spp.	--	--	.97	.84	.67	.43	.79
Eubosmina coregoni	--	--	.94	--	-.82	-.07	.97
Minor cladocerans	--	--	.37	-.80	.03	-.25	--
Asplanchna spp.	--	--	-.43	.73	-.12	.07	.96
Station Depth	-.48	.93	.80	.67	.81	.79	-.92
Total Zooplankton	.63	.68	.84	.46	-.23	.21	.29

-- Taxa not included in the analysis.

The second principal component (PC2) was not identified. PC2 generally had low correlations with station depth. As for PC1, correlations of PC2 with total zooplankton varied widely ($0.2 < |r| < 0.9$, Table 3). Note that the sign of the correlations between the principal components and depth or total zooplankton

Table 3. Correlations (r) between zooplankton (log #/m^3 + 1) taxa used in the analyses, station depth, total zooplankton and the second principal component.

Taxon	April 1977	April 1978	July 1977	July 1978	October 1977	October 1978	December 1977
Copepod nauplii	.82	.23	.44	-.01	-.23	.57	.24
Cyclopoid copepods C1-C5	-.67	-.05	-.04	.78	.40	.65	.80
Cyclops spp. C6	-.04	-.06	-.08	.60	.69	.62	.55
Tropocyclops prasinus m. C1-C6	--	--	--	--	.83	.59	.76
Diaptomus spp. C1-C5	.72	.06	.02	.24	.43	.42	.88
Diaptomus spp. C6	.37	.31	-.00	.41	.17	.37	.85
Epischura lacustris C1-C6	--	--	.76	--	.28	.44	--
Eurytemora affinis C1-C6	--	--	.84	.19	.09	-.13	--
Limnocalanus macrurus C1-C6	.41	.99	--	.28	--	--	.75
Bosmina longirostris	--	--	.77	.43	.17	.29	.13
Daphnia spp.	--	--	.09	.34	.55	.78	.47
Eubosmina coregoni	--	--	.18	--	.32	.73	.10
Minor cladocerans	--	--	.16	.59	.65	.47	--
Asplanchna spp.	--	--	.70	.73	.83	.76	.12
Station Depth	-.60	-.11	-.45	.47	-.13	-.36	.25
Total Zooplankton	.75	.43	.38	.62	.18	.82	.85

-- Taxa not included in the analysis.

densities is an artifact of the analysis and has little interpretative meaning. Only the strength of these correlations is important. However, the sign of the correlations between principal components and the transformed taxa densities actually used in an analysis is important in defining assemblages of

zooplankton. There was no evidence that geographic location *per se* was an important factor either for PC1 or PC2. Stations located in similar depths of water and in close geographic proximity often were distant neighbors on the ordination graphs. There was no evidence that zooplankton populations in the northern half of the survey grid were distinct from populations in the south.

April

Although PC1 was strongly related to depth in the April 1978 analysis, there was a relatively weak relationship between PC1 and depth for the April 1977 analysis (Table 2 and Fig. 22). By the April 1977 cruise, lake warming had proceeded to a moderate extent. Most taxa used in the analysis were more abundant inshore, with the exception of immature cyclopoid copepodites (Figs. 23a and 24). In contrast, little warming of the inshore region had occurred by the April 1978 cruise and most taxa had lowest mean abundances in the 5-10 m depth zone (Fig. 23b). All taxa in the analysis had positive correlations with PC1, indicating that PC1 represents zooplankton abundance as well as station depth for April 1978 (Table 2).

The previous analyses of April data (Evans 1975, Evans *et al*. 1978) have shown generally weak relationships between PC1 and depth and that the strength of the relationship depended upon the extent of lake warming. There was no evidence from principal component analysis that stations located in or near the thermal plume had zooplankton population structures which were different from those at stations located upcurrent and downcurrent of the plume.

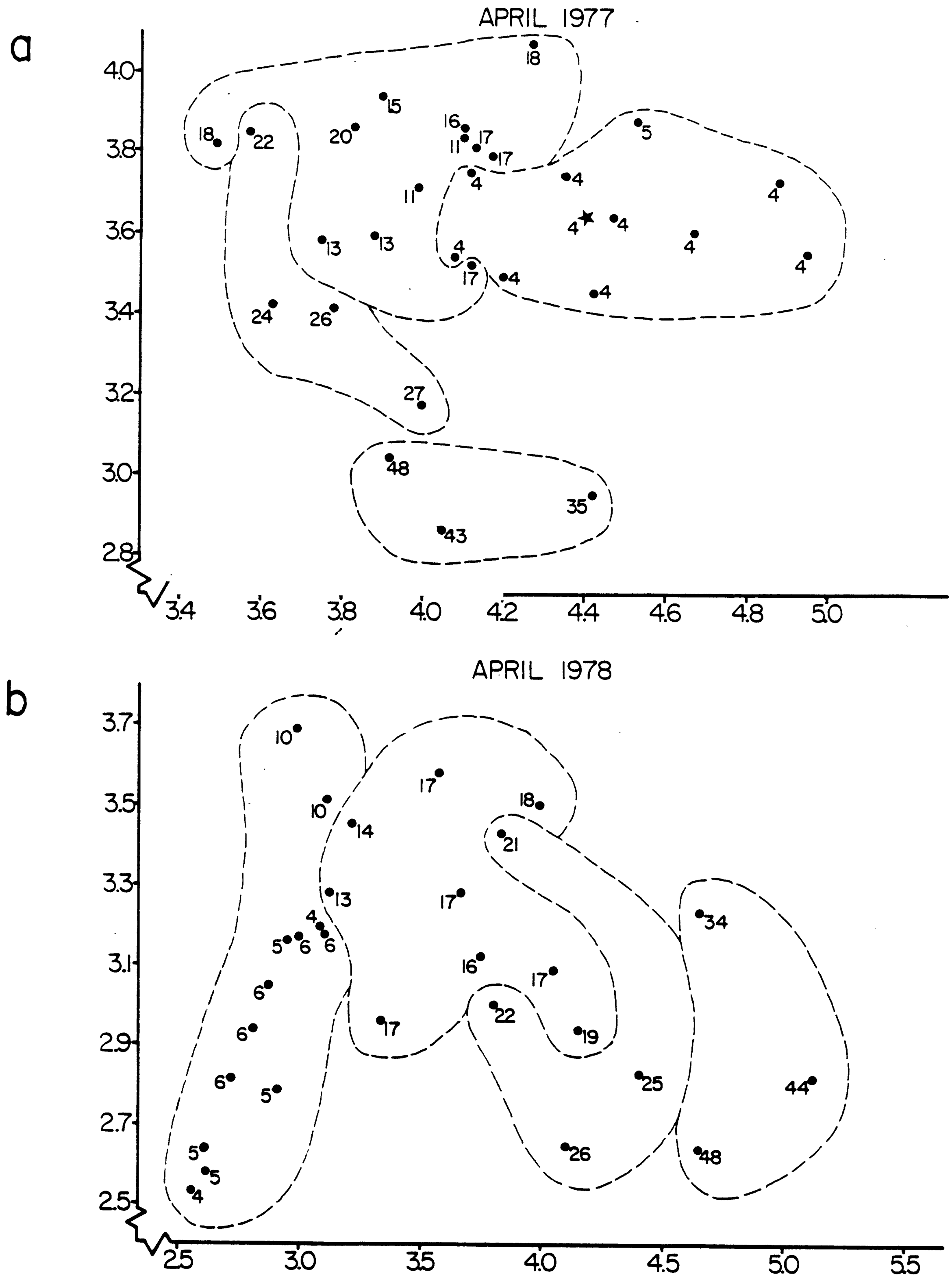

FIG. 22. Principal component ordination of survey stations sampled on a) 14 April 1977, b) 12 April 1978. Station depth (m) is noted next to each point. Dotted lines roughly separate stations of three depth intervals: 5-10 m, 10-20 m, and 20-50 m. ✶ indicates stations in the thermal plume.

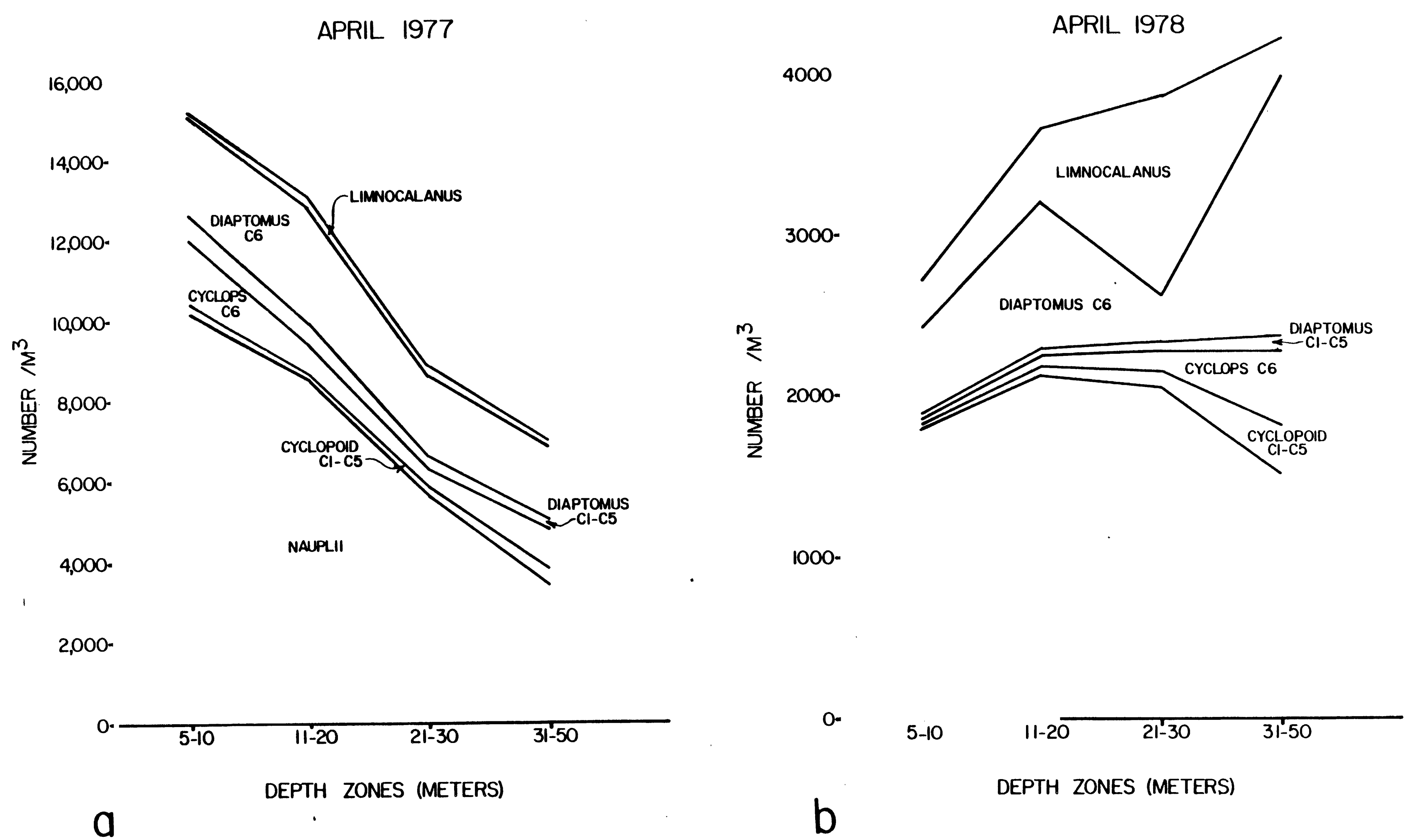

FIG. 23. Mean densities of zooplankton taxa for four depth zones (5-10 m, 10-20 m, 20-30 m, and 30-50 m). a) 14 April 1977, b) 12 April 1978.

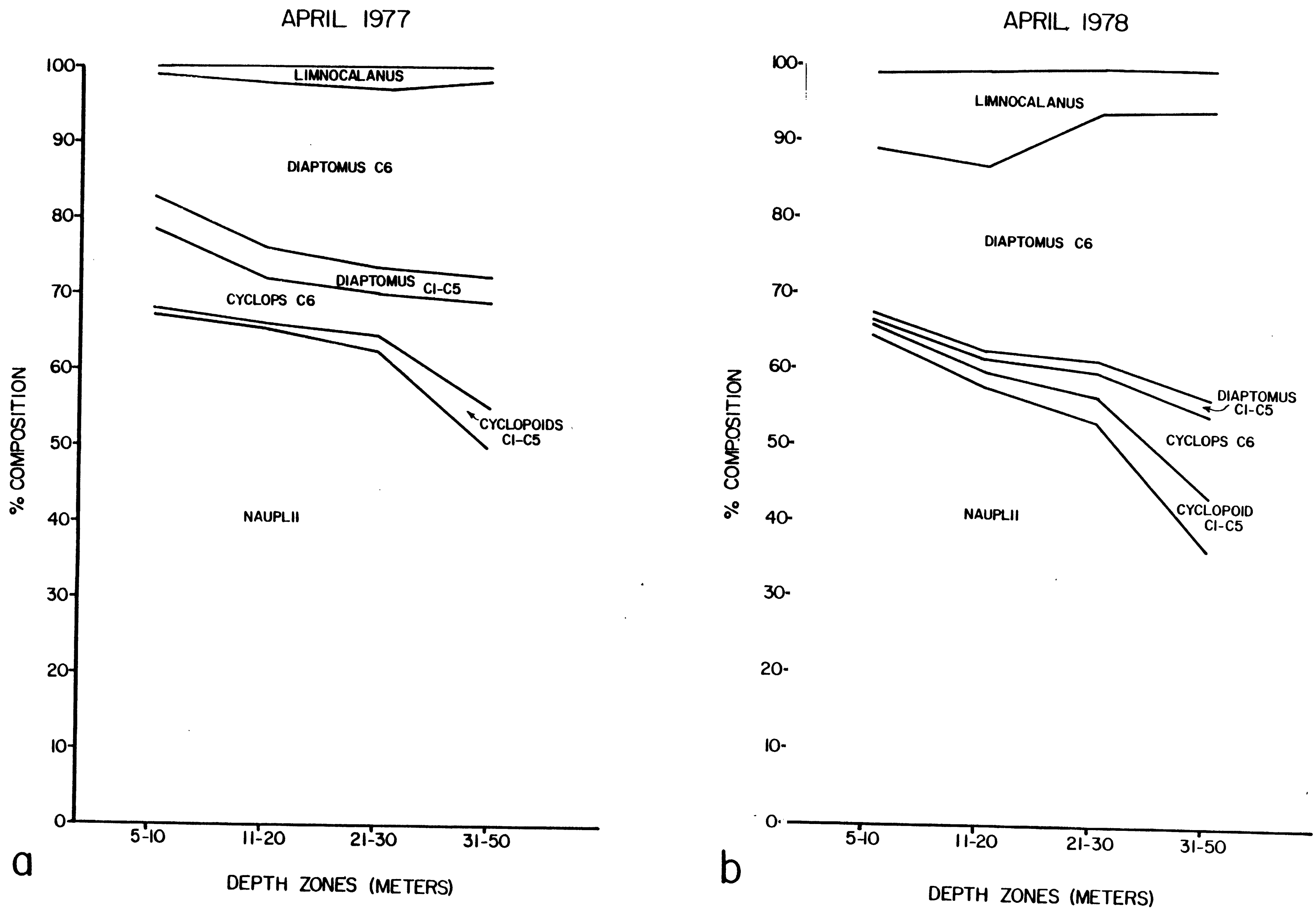

FIG. 24. Mean composition of zooplankton taxa for four depth zones (5-10 m, 10-20 m, 20-30 m, and 30-50 m). a) 14 April 1977, b) 12 April 1978.

July

In the July 1977 and 1978 analyses, PC1 was highly correlated with station depth (Table 2). The ordination of stations by their PC1 and PC2 scores shows a distinct clustering of stations by depth (Fig. 25).

The two zooplankton assemblages defined by PC1 in July 1977 included an inshore assemblage of Epischura lacustris copepodites, Eurytemora affinis copepodites, and Asplanchna spp. (Table 2 and Figs. 26a and 27a). The other assemblage was an offshore one characterized by Cyclops spp. copepodites, Diaptomus spp. copepodites, Daphnia spp., and Eubosmina coregoni. In July 1978, the inshore assemblage defined by PC1 consisted of copepod nauplii, Eurytemora affinis copepodites, and "minor" cladocerans (representing Chydorus sphaericus primarily), while the offshore assemblage was characterized by Cyclops spp. adults, Limnocalanus macrurus copepodites, Bosmina longirostris, Daphnia spp., and Asplanchna spp. (Table 2 and Figs. 26b and 27b). Bosmina longirostris and Asplanchna spp. are typically associated with inshore waters during stratified periods (Evans et al. 1978, Evans et al. 1980). Their unusual characterization as members of an offshore assemblage in July 1978 reflects the disruption of the inshore waters by an upwelling at the time of the cruise (discussed earlier). There was no evidence from principal component analysis that stations located in or near the thermal plume had zooplankton population structures which were different from those at stations located upcurrent and downcurrent of the plume.

October

The October 1977 and 1978 analyses gave strong correlations between PC1 and depth (Table 2). The ordination of stations by their PC1 and PC2 scores shows a clustering of stations by depth (Fig. 28).

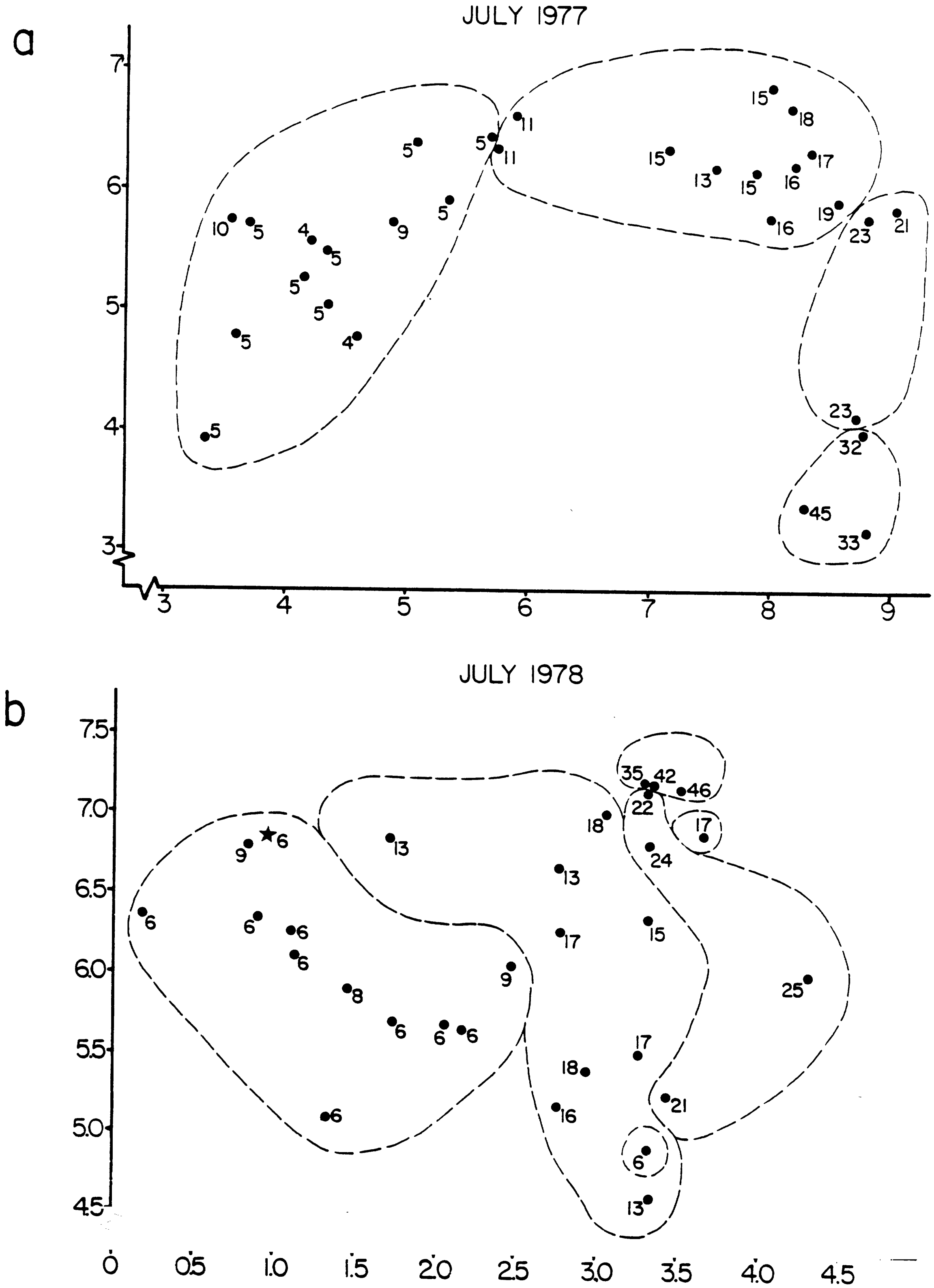

FIG. 25. Principal component ordination of the survey stations sampled on a) 13 July 1977, b) 12 July 1978. ✶ indicates stations in the thermal plume.

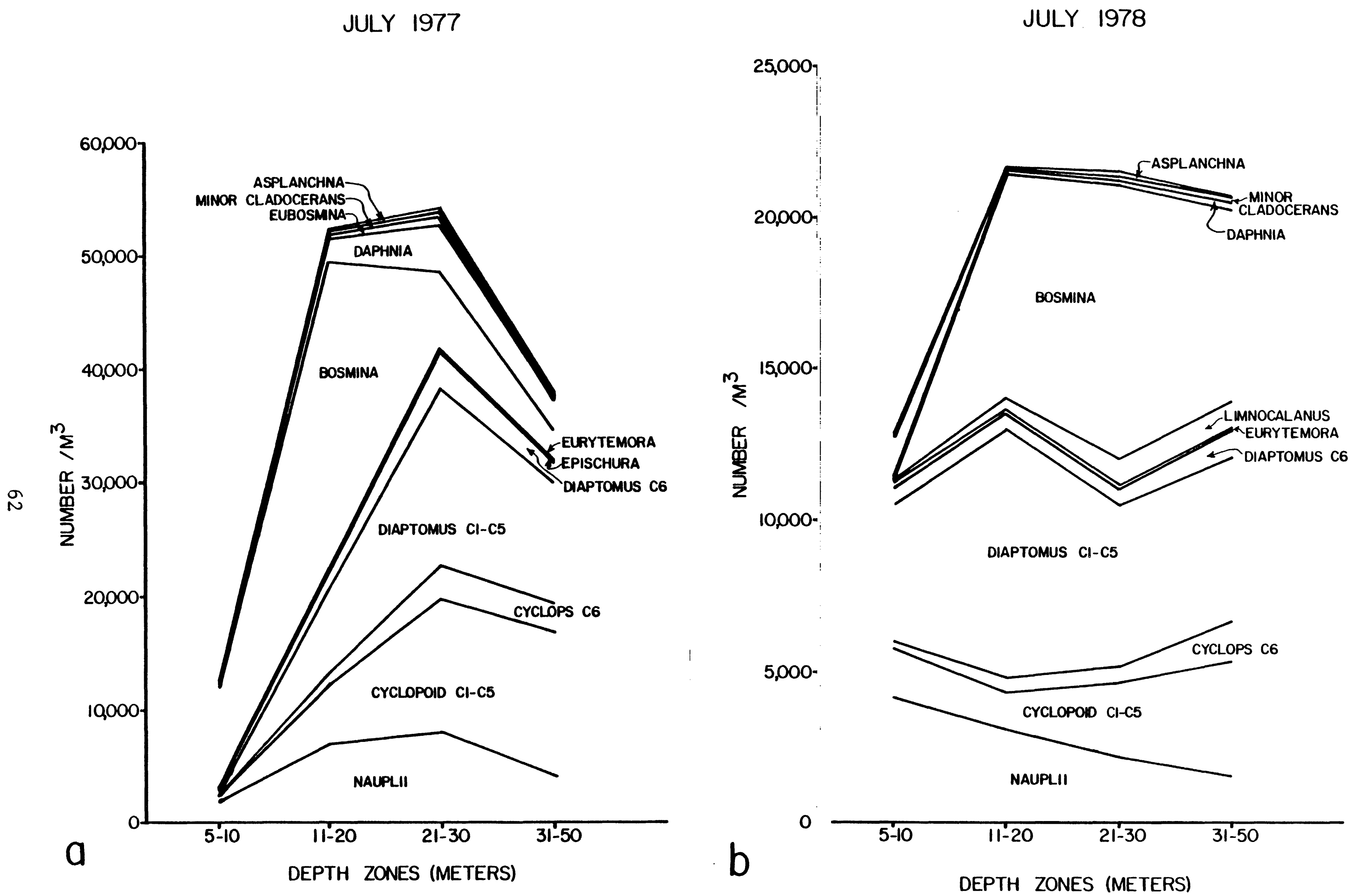

FIG. 26. Mean densities of zooplankton taxa for four depth zones (5-10 m, 10-20 m, 20-30 m, and 30-50 m). a) 13 July 1977, b) 12 July 1978.

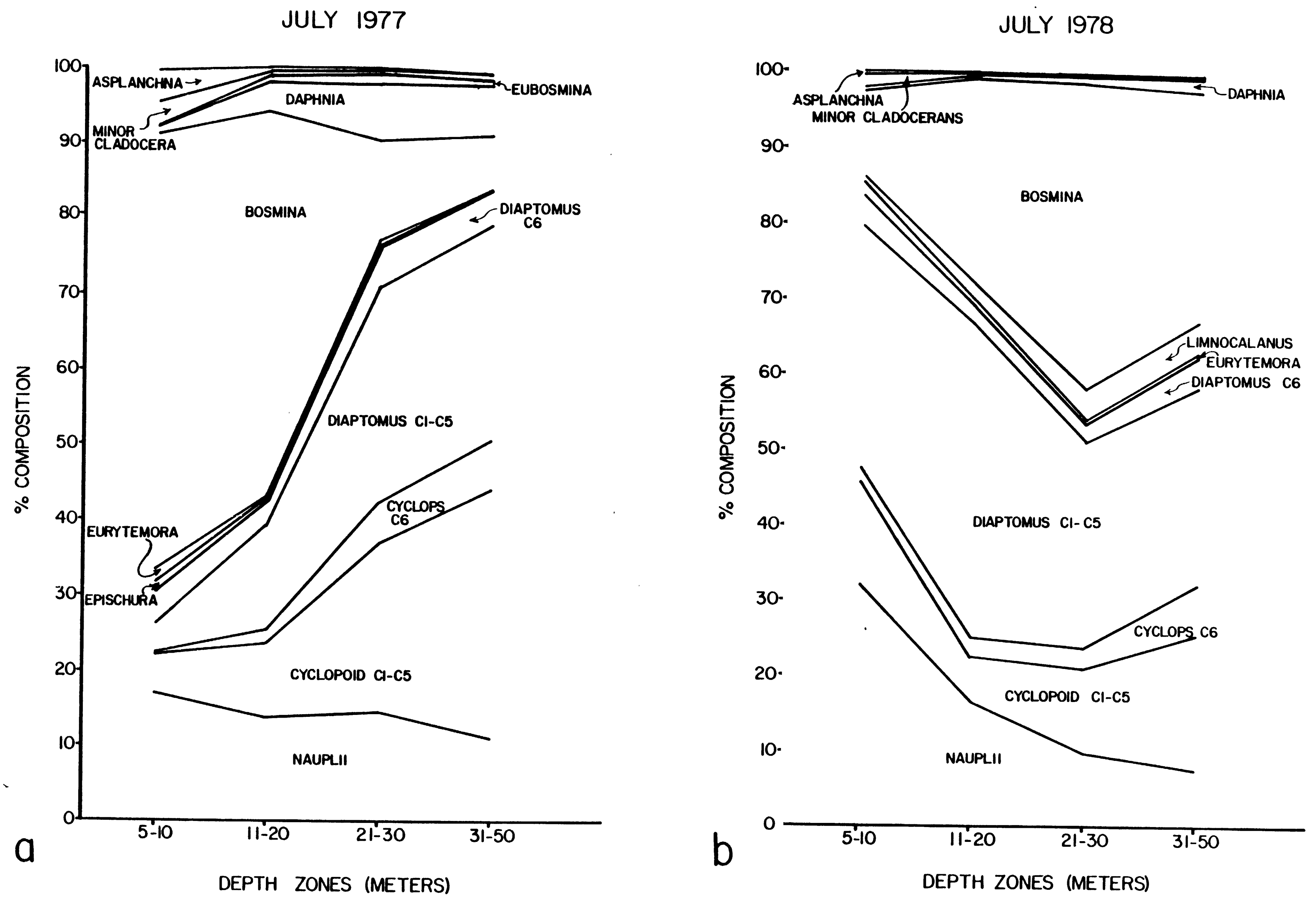

FIG. 27. Mean composition of zooplankton taxa for four depth zones (5-10 m, 10-20 m, 20-30 m, and 30-50 m). a) 13 July 1977, b) 12 July 1978.

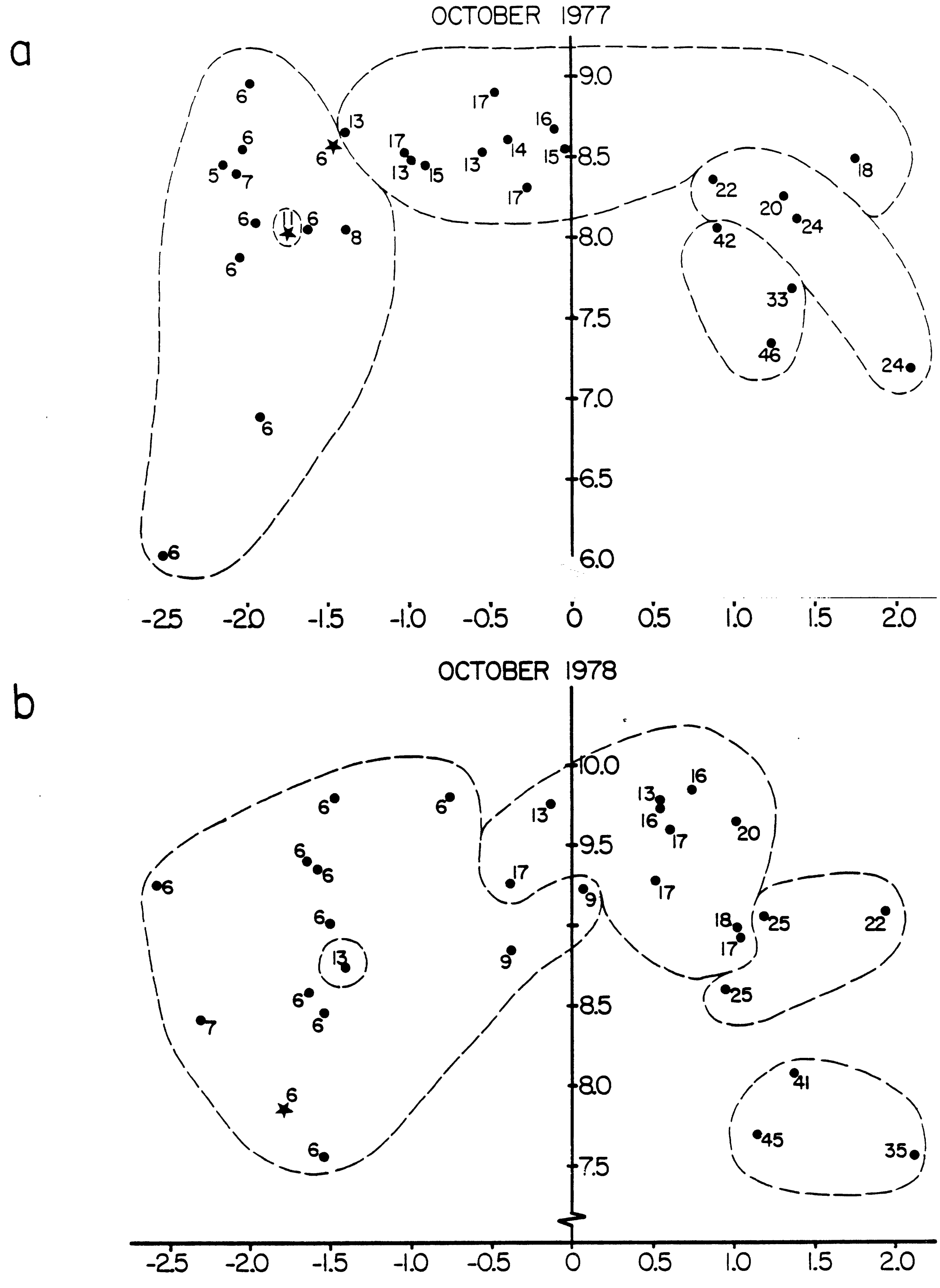

FIG. 28. Principal component ordination of the survey stations sampled on a) 14 October 1977, b) 11 October 1978. ✶ indicates stations in the thermal plume.

The inshore zooplankton assemblage defined by PC1 in the October 1977 analysis consisted of Epischura lacrustis, Eurytemora affinis, Bosmina longirostris, and Eubosmina coregoni (Table 2 and Figs. 29a and 30a). The offshore community was represented by immature cyclopoid copepodites, Diaptomus spp. copepodites, and Daphnia spp. (Table 2 and Figs. 29a and 30a). In October 1978, the inshore assemblage defined by PC1 consisted of copepod nauplii, Eurytemora affinis, and Bosmina longirostris, while the offshore assemblage was characterized by Cyclops spp. adults, Diaptomus spp. copepodites, and Daphnia spp. (Table 2 and Figs. 29b and 30b).

December

PC1 was strongly correlated with depth in the December 1977 analysis (Table 2). Ordination of stations by their PC1 and PC2 scores provides a clustering of stations by depth (Fig. 31).

The inshore assemblage defined by PC1 consists of Cyclops spp. adults, Bosmina longirostris, Daphnia spp., Eubosmina coregoni, and Asplanchna spp. (Table 2 and Figs. 32 and 33). The offshore assemblage was represented mainly by Limnocalanus macrurus copepodites.

DISCUSSION

Zooplankton populations in the vicinity of the survey area in 1977 and 1978 followed similar distribution patterns as in previous years. Spring zooplankton were dominated by adult Diaptomus ashlandi, D. sicilis, Cyclops bicuspidatus thomasi, and Limnocalanus macrurus (Table 4). These reproduced, giving rise to large numbers of nauplii which, through May and June, developed into immature

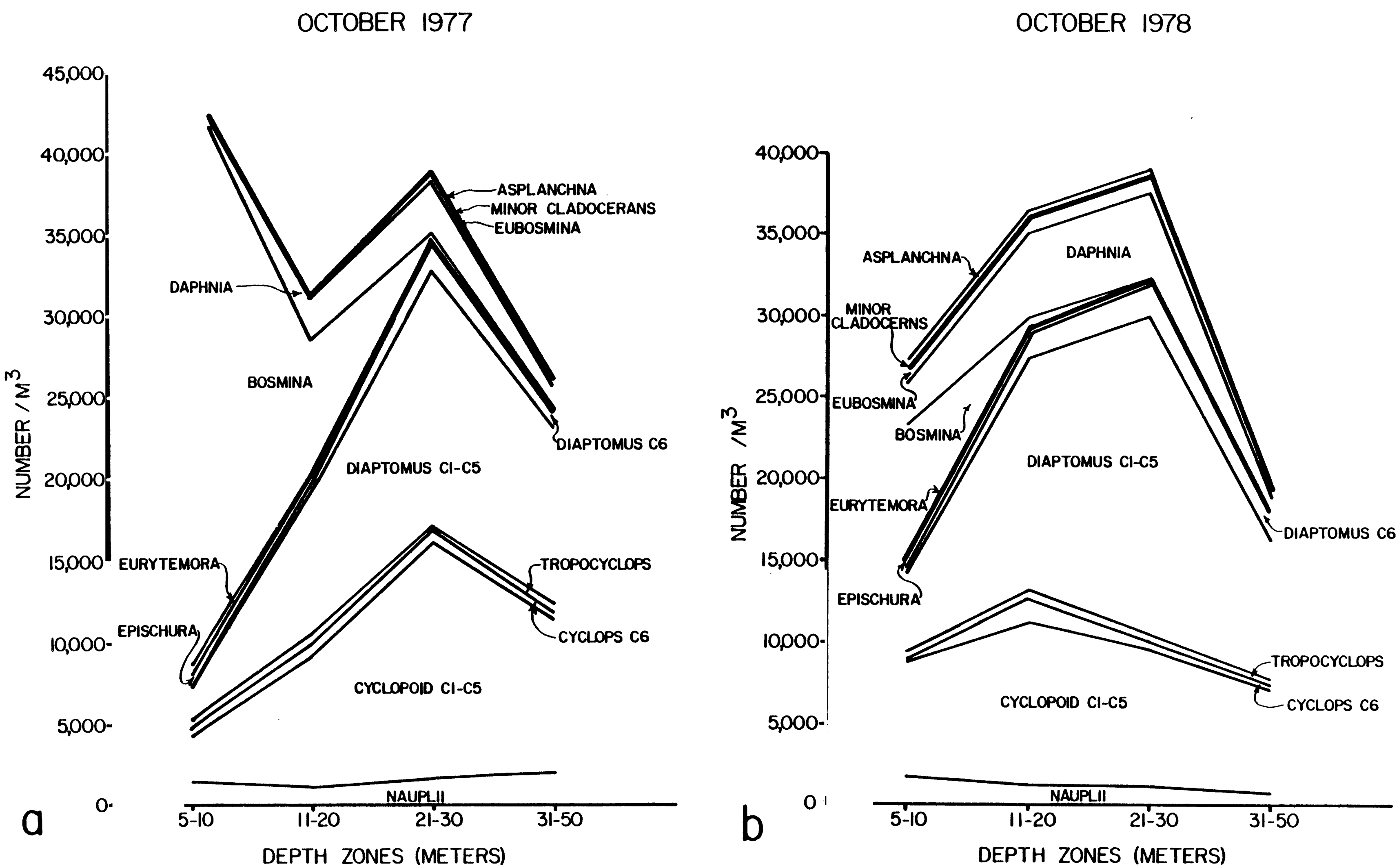

FIG. 29. Mean densities of zooplankton taxa for four depth zones (5-10 m, 10-20 m, 20-30 m, and 30-50 m). a) 14 October 1977, b) 11 October 1978.

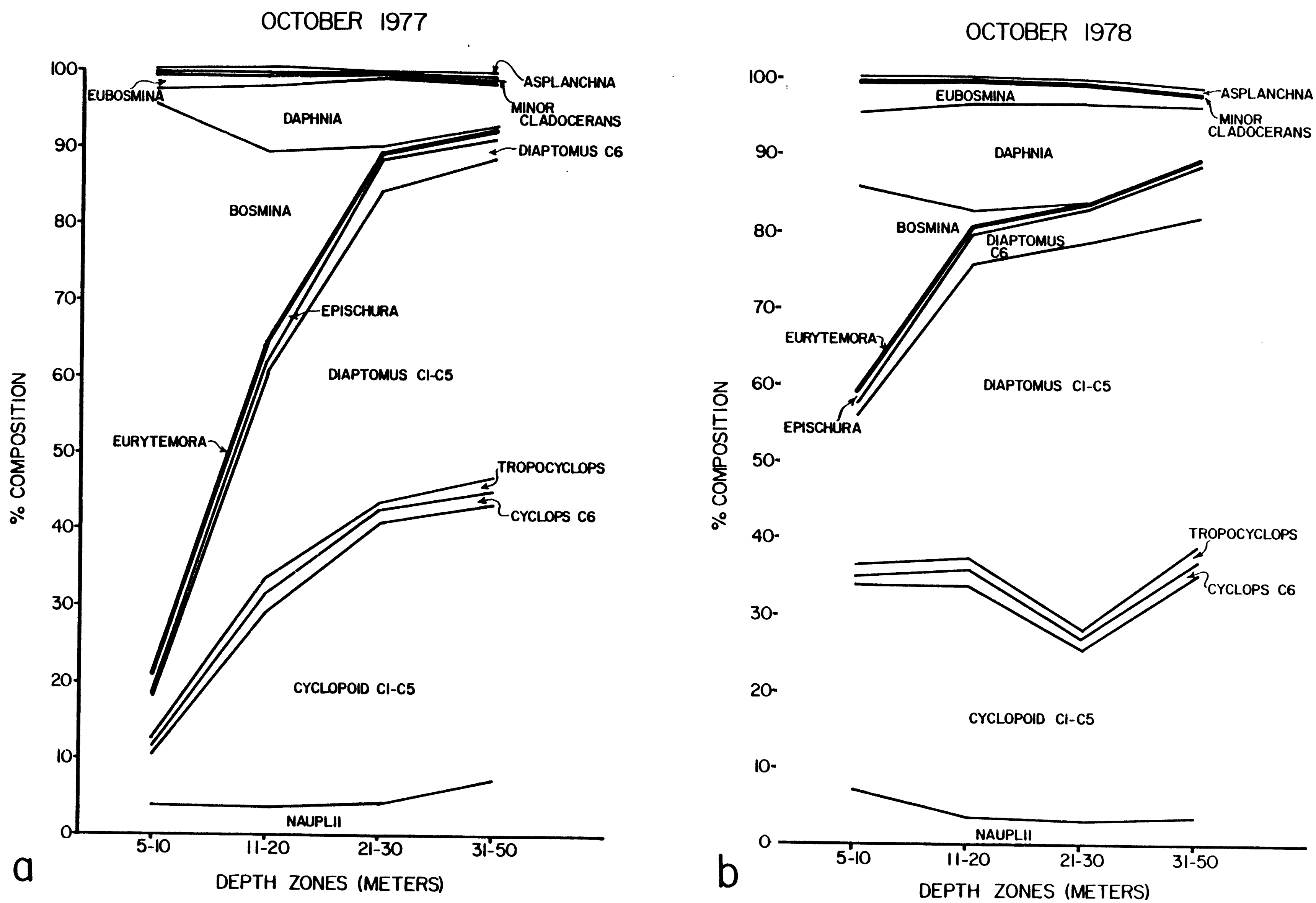

FIG. 30. Mean composition of zooplankton taxa for four depth zones (5-10 m, 10-20 m, 20-30 m, and 30-50 m). a) 14 October 1977, b) 11 October 1978.

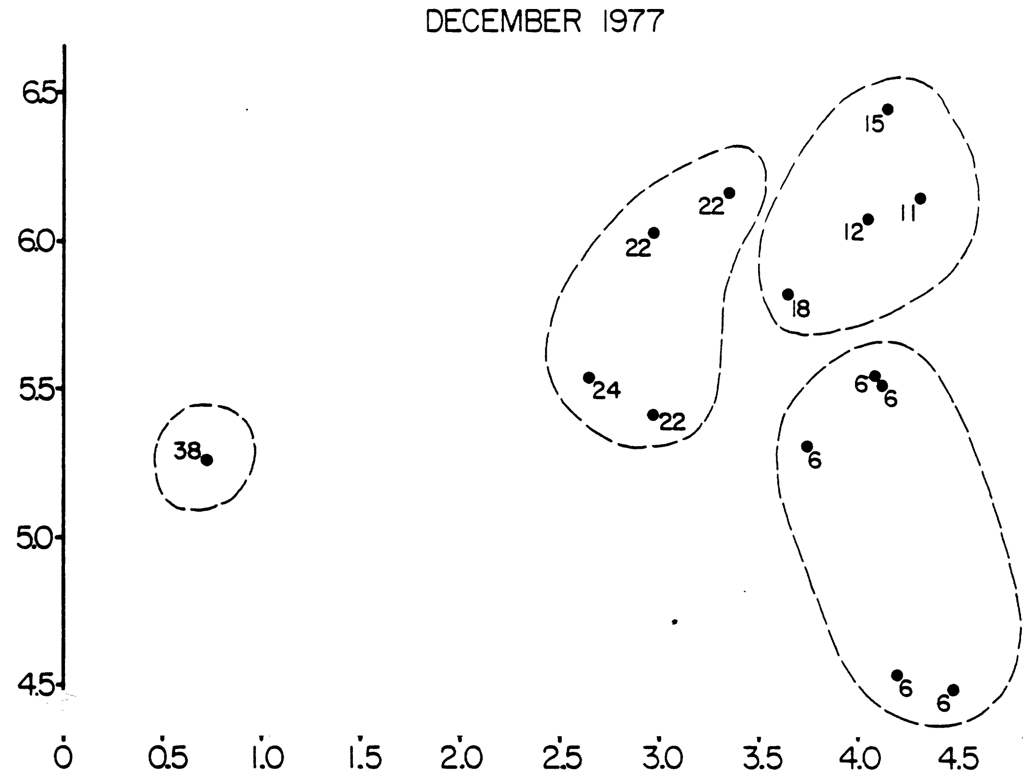

FIG. 31. Principal component ordination of the survey stations sampled on 15 December 1977.

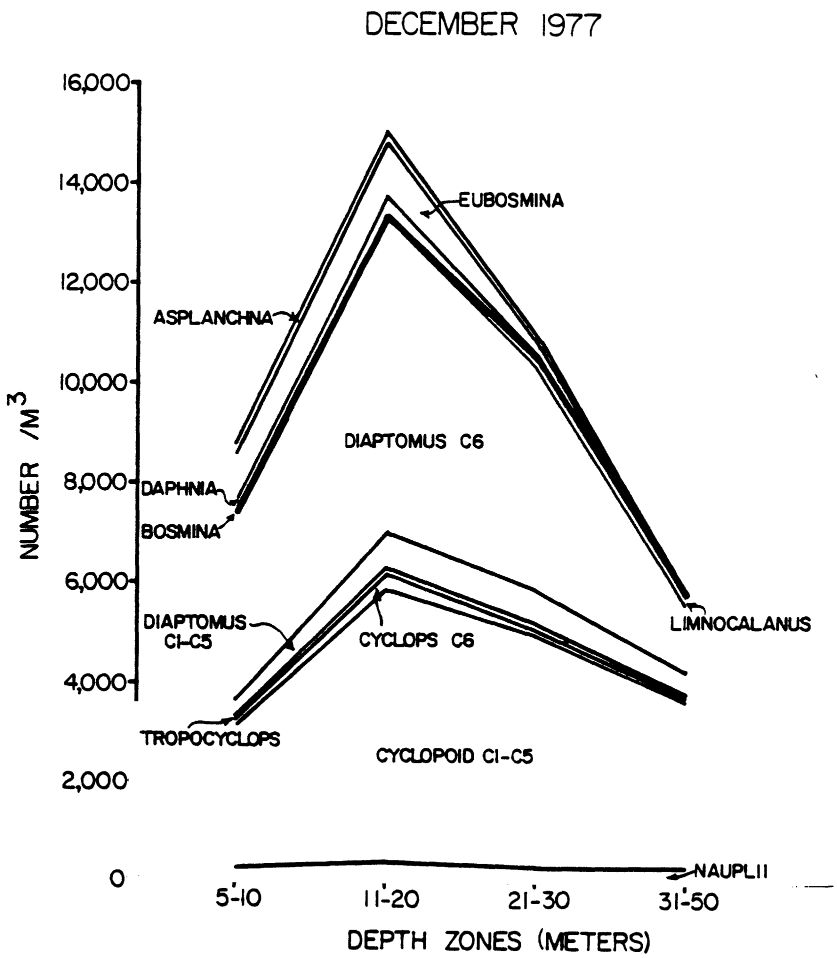

FIG. 32. Mean densities of zooplankton taxa for four depth zones (5-10 m, 10-20 m, 20-30 m, and 30-50 m) on 15 December 1978.

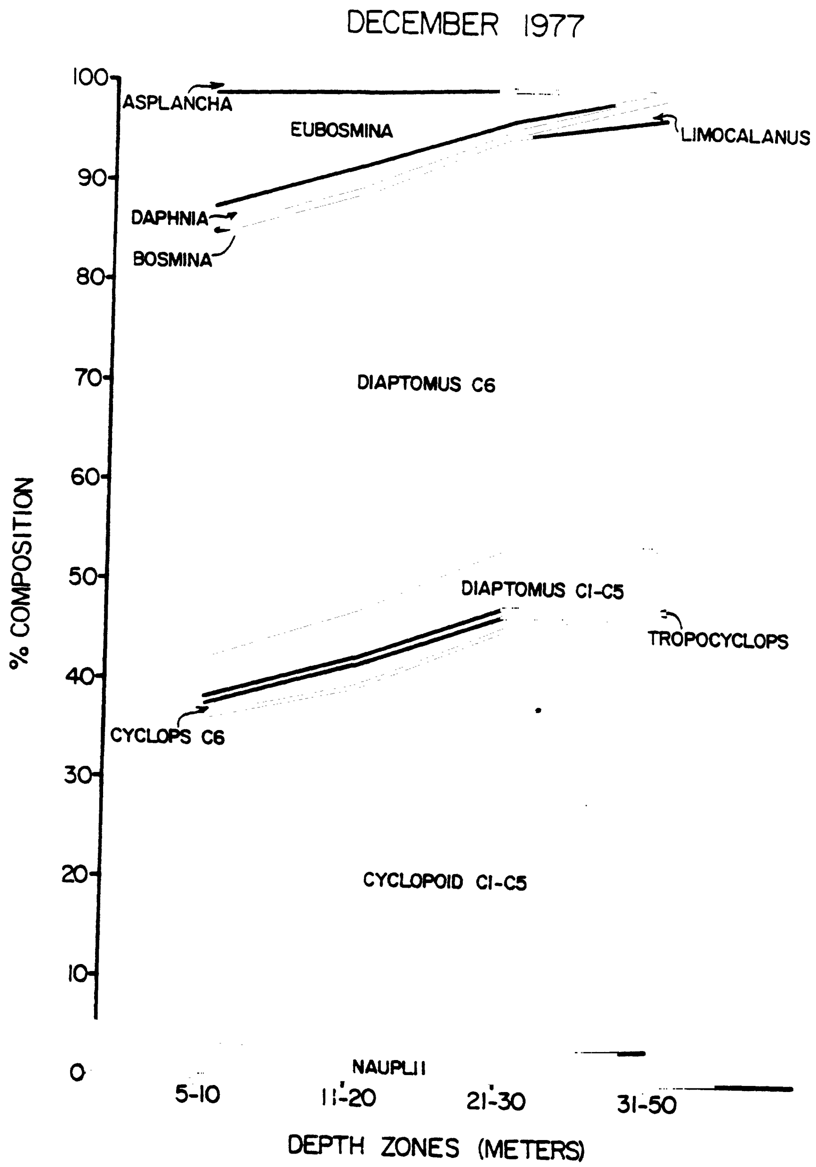

FIG. 33. Mean composition of zooplankton taxa for four depth zones (5-10 m, 10-20 m, 20-30 m, and 30-50 m) on 15 December 1978.

Table 4. Mean seasonal density of zooplankton in each of four depth zones during 1977-1978. Spring = April and May; Summer = June, July, and August; Fall = September and October; Winter = December (1977 only). tr $\leq$ 0.5/m^3.

	INSHORE ZONE #/m^3 (5-10 m depth)				MIDDLE ZONE #/m^3 (10-20 m depth)			
TAXA	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
Copepod nauplii	5,859	3,462	2,818	280	6,187	4,992	2,048	386
Cyclops spp. C1-C5	778	2,710	6,122	2,825	959	4,597	8,544	5,459
Cyclops bicuspidatus thomasi C6	499	183	380	133	410	900	632	323
Cyclops vernalis C6	tr	10	13	1	1	12	20	20
Paracyclops fimbriatus poppei C1-C6	0	0	0	tr	0	0	0	0
Mesocyclops edax C1-C6	0	0	49	0	0	0	90	0
Eucyclops spp. C1-C6	tr	tr	0	0	tr	0	tr	0
Tropocyclops prasinus mexicanus C1-C6	1	42	394	60	1	77	482	110
Diaptomus spp. C1-C5	927	2,447	3,941	358	1,282	7,227	9,726	705
Diaptomus ashlandi C6	717	156	425	2,370	1,109	535	558	3,449
Diaptomus minutus C6	108	210	260	563	156	407	289	791
Diaptomus oregonensis C6	21	10	415	406	27	32	337	1,116
Diaptomus sicilis C6	148	22	131	370	342	64	253	928
Epischura lacustris C1-C6	40	61	484	2	13	101	367	2
Eurytemora affinis C1-C6	7	494	225	2	1	274	84	0
Limnocalanus macrurus C1-C6	209	38	1	9	561	135	3	37
Senecella calanoides C1-C6	0	0	0	0	0	0	tr	0
Harpacticoids	10	1	tr	1	5	0	tr	1
Bosmina longirostris	315	22,497	17,002	35	307	26,886	4,426	37
Eubosmina coregoni	5	47	1,789	986	3	175	1,006	1,093
Daphnia retrocurva	4	304	666	1	17	1,001	1,436	15
Daphnia galeata mendotae	4	42	706	184	14	110	1,572	343
Daphnia longiremus	0	0	0	0	0	0	0	0
Ceriodaphnia spp.	0	146	172	0	0	50	37	0
Alona spp.	0	0	0	0	0	0	0	0
Chydorus sphaericus	10	90	89	tr	1	24	12	0
Disparalona rostrata	0	tr	1	0	0	0	0	0
Diaphanosoma spp.	0	17	74	0	tr	50	51	0
Macrothrix laticornis	1	tr	tr	0	tr	0	tr	0
Leydigia quadrangularis	tr	0	0	0	0	0	0	0
Eurycercus lamellatus	tr	4	2	0	tr	10	tr	0
Ilyocryptus spp.	tr	tr	tr	0	0	0	0	0
Latona setifera	0	0	0	0	0	0	0	0
Sida crystallina	0	0	0	0	0	0	0	0
Polyphemus pediculus	1	93	4	0	0	73	14	0
Holopedium gibberum	0	10	14	0	0	22	12	0
Leptodora kindtii	tr	3	22	0	0	9	26	0
Asplanchna spp.	64	2,046	221	83	10	790	233	92
Total Zooplankton	9,730	35,144	36,427	8,670	11,408	48,552	32,270	14,905

(continued).

Table 4. Concluded.

TAXA	INNER OFFSHORE ZONE #/m^3 (20-30 m depths) Spring	Summer	Fall	Winter	OUTER OFFSHORE ZONE #/m^3 (30-45 m depths) Spring	Summer	Fall	Winter
Copepod nauplii	7,902	5,264	1,635	279	3,753	3,905	1,145	259
Cyclops spp. C1-C5	2,657	6,729	7,620	4,653	311	7,222	6,350	3,410
Cyclops bicuspidatus thomasi C6	712	2,082	508	135	746	1,870	328	20
Cyclops vernalis C6	1	7	7	2	1	2	2	0
Paracyclops fimbriatus poppei C1-C6	0	0	0	0	0	0	0	2
Mesocyclops edax C1-C6	0	1	67	0	0	0	28	0
Eucyclops spp. C1-C6	0	0	0	0	0	0	0	0
Tropocyclops prasinus mexicanus C1-C6	4	72	327	91	7	27	352	54
Diaptomus spp. C1-C5	3,698	12,062	11,972	666	522	10,133	7,958	468
Diaptomus ashlandi C6	866	1,049	991	2,677	1,080	938	396	2,038
Diaptomus minutus C6	287	794	537	531	159	526	217	358
Diaptomus oregonensis C6	28	97	530	558	52	104	246	110
Diaptomus sicilis C6	308	105	646	774	210	127	466	878
Epischura lacustris C1-C6	6	81	201	3	2	34	161	0
Eurytemora affinis C1-C6	3	174	10	0	0	49	6	0
Limnocalanus macrurus C1-C6	1,098	548	63	61	235	607	232	176
Senecella calanoides C1-C6	0	0	0	0	0	0	0	0
Harpacticoids	1	0	0	0	0	0	1	1
Bosmina longirostris	698	12,956	465	9	2	5,700	162	1
Eubosmina coregoni	7	249	460	329	0	145	279	15
Daphnia retrocurva	94	1,710	723	0	1	895	303	0
Daphnia galeata mendotae	18	528	1,365	111	tr	625	778	27
Daphnia longiremus	0	0	0	0	0	0	0	0
Ceriodaphnia spp.	2	36	11	0	0	2	0	0
Alona spp.	0	0	0	0	0	0	0	0
Chydorus sphaericus	1	3	6	0	0	0	2	0
Disparalona rostrata	0	0	0	0	0	0	0	0
Diaphanosoma spp.	0	45	61	0	0	8	21	0
Macrothrix laticornis	0	0	0	1	0	0	0	0
Leydigia quadrangularis	0	0	0	0	0	0	0	0
Eurycercus lamellatus	0	0	0	0	0	0	0	0
Ilyocryptus spp.	0	0	0	0	0	0	0	0
Latona setifera	0	0	0	0	0	0	0	0
Sida crystallina	0	0	0	0	0	0	0	0
Polyphemus pediculus	0	59	tr	0	0	39	0	0
Holopedium gibberum	1	44	3	0	0	30	1	0
Leptodora kindtii	1	20	19	0	0	20	15	0
Asplanchna spp.	4	871	138	33	0	184	88	0
Total Zooplankton	18,398	45,592	28,371	10,910	7,080	33,188	19,538	7,818

copepodites and then into adults. Copepod reproduction continued through the summer and well into the autumn. Cladocerans were rare in spring but increased markedly in numbers and dominance through the summer with *Bosmina longirostris* the summer dominant (Table 4). This species also was an autumn dominant along with *Eubosmina coregoni*, *Daphnia retrocurva*, and *D. galeata mendotae*. By late autumn, copepods again dominated the zooplankton with overwintering immature *Cyclops bicuspidatus thomasi* copepodites and adult *Diaptomus ashlandi*, *D. minutus*, *D. oregonensis*, *D. sicilis*, and *Limnocalanus macrurus* the numerically dominant forms.

While zooplankton differed somewhat in abundance and composition between 1977 and 1978, differences were not major. Some differences clearly were associated with climatic events such as differences in warming during the spring months (April and May) of the two years. Other differences could be related to physical events such as upwellings. As in previous years, abundance and biomass isopleths generally paralleled shore. Such depth-related differences in zooplankton distributions have been related to the interaction of several factors including water temperature, currents, phytoplankton standing stocks, and predation (Watson and Wilson 1978, Watson and Carpenter 1974, and Evans *et al*. 1980).

Zooplankton distributions in the vicinity of the power plant were similar to those at upcurrent and downcurrent stations. However, substantial differences were observed on some cruises. Some, such as the low concentrations of *Asplanchna* spp. in the vicinity of the plant and the down-current control stations (June 16, 1977), were due to an upwelling event which transported these epilimnetic nearshore zooplankton away from shallower areas of the survey grid.

Other differences, such as the high Bosmina longirostris concentrations ($294,000/m^3$) over the discharge jets and low concentrations to the south and north on August 10, 1978, have no ready explanation.

As discussed in the last operational report (Evans et al. 1978), the lake monitoring study is not adequately designed to detect alterations in zooplankton populations in the immediate vicinity of the discharge jets. Nor does a mechanism appear to exist which could produce biologically detectable and significant alterations in zooplankton populations. This is further elucidated in the following paragraphs.

Previous condenser passage studies and results of studies reported in section 3 indicate that only a small percentage of zooplankton is killed by plant passage. This percentage is less than 12% and probably closer to 1 or 2%. Mechanical stresses, rather than thermal shock, are the more significant cause of mortality. Heated discharge water with its small percentage of dead zooplankton is rapidly diluted in the lake to approximately 30% in minutes (assuming an in-plant temperature of 10C° and a temperature of 3C° over the discharge jets). Intense vertical mixing prevents this small percentage (30% x 12% = 4%) of zooplankton from settling from the water column. Even if these zooplankton were to settle immediately from the water, a 4% loss could not be detected. The coefficient of variation between replicate net hauls approaches 10% while the coefficient of variation between stations located in the same depth of water reaches 50%. Currently employed sampling techniques are not sensitive enough to detect a loss as small as 4% at one station.

High concentrations of Bosmina longirostris have been observed previously in the vicinity of the discharge jets. Such occasions include the September

1976 plume study (Evans *et al.* 1978) and the August 1978 cruise. *Asplanchna* spp. concentrations also have been high on occasion (July 1975, July 1976 cruises). The reasons for these occurrences is not known.

Temperatures in the thermal plume are only 2 or 3C° above ambient for a period of less than an hour and 1.7C° above ambient for less than 3 hours. A general Q10 for biological functions is 2. Thus zooplankton, which require 14 days to complete a generation at 10°C, require approximately 7 days at 20°C. An increase in water temperature of 2C° would thus decrease generation time by only 10% versus 50% with a 10C° increase. Fecundity is unaffected by temperature, with egg production more a function of food level.

Rotifer generation times at 20°C are in the order of 2 days while cladoceran generation times at the same temperature are several days (Allen 1976). Consequently, short exposures to thermal plumes only slightly warmer than ambient waters are unlikely to have a significant effect on zooplankton developmental rates (except possibly for rotifers) or r, the rate of population increase. Thus, the high densities of *Bosmina longirostris* and *Asplanchna* spp. in the vicinity of the plume remain unexplained. Future research into this problem should investigate plume hydraulics to determine the actual residence time of water and zooplankton in this area. This could determine whether circulation patterns are such that zooplankton are artificially concentrated in this area, just as Langmuir cells produce localized increased concentrations of zooplankton (Wetzel 1975).

Two new species occurrences were noted in 1978. The first, *Daphnia parvula*, was observed at a few stations in May 1978 and continues to be observed, although infrequently. This species typically is associated with

ponds and small lakes in more southern locales (Brooks 1957). *Daphnia pulex* was observed at several stations during both the October and November 1978 cruises. This species is not a typical component of Great Lakes zooplankton, although it has been found in highly eutrophic shallow areas such as Green Bay (Gannon 1972). This species has been eliminated from certain ponds by size-selective fish predators (Galbraith 1967).

Mesocyclops edax was observed in increased abundances in October and November 1978 with concentrations approaching those observed by Wells (1960) in 1955 before the alewife population explosion. Wells observed that this relatively large cyclopoid copepod was severely reduced in numbers by alewife populations in southeastern Lake Michigan and was considerably less abundant by 1966. *Mesocyclops edax* is more common in shallow eutrophic regions of the Great Lakes such as Green Bay and Lake Erie (Gannon 1972, Patalas 1972). Its increased occurrence and the new occurrence of *Daphnia pulex* in the fall of 1978 cannot be accounted for at this time. However, they may be related to increased eutrophication of the southern basin (Chapra and Robertson 1977) or alterations in the size of the planktivorous fish population.

SECTION 2

EVALUATION OF LONG-TERM TRENDS OF THE EFFECTS OF POWER PLANT OPERATION (1975-1978) ON ZOOPLANKTON POPULATIONS

INTRODUCTION

There are two levels of concern regarding the environmental effects of power plant operation. First, power plant operation may produce localized alterations in zooplankton populations in the immediate discharge area. Second, power plant influence could extend over a wider area and affect a substantial portion of the lake: such effects are likely to be subtle in nature.

In Section 1, we examined the 1977 and 1978 field survey data for evidence of gross alterations in zooplankton populations in the vicinity of the plume. With the possible exception of *Bosmina longirostris* and *Asplanchna* spp. distributions in some summer and autumn months, no evidence of gross alterations was observed. As was discussed in Section 1, there is no apparent mechanism by which power plant operation could produce biologically significant alterations in zooplankton populations in the immediate vicinity of the plume.

Some evidence for possible trends of long-term change were noted in October and November 1978. *Daphnia pulex*, a cladoceran associated with eutrophic areas of the Great Lakes (Gannon 1972) and a species which has been eliminated from small ponds by planktivorous fish (Galbraith 1967), was observed for the first time in October and November 1978. *Mesocyclops edax*, a cyclopoid which was relatively more abundant in southeastern Lake Michigan prior to the mid-1960s alewife population explosion (Wells 1970), was observed in increased numbers during the October and November 1978 cruises. These abundances were similar to those observed by Wells (1960) in 1955.

In this section, we evaluate the preoperational and operational data base for evidence of long-term changes in zooplankton populations. The monitoring program for the Donald C. Cook Nuclear Power Plant was designed for such an analytical approach spanning several years of preoperational and operational monitoring and extending over a large area (250 km^2 of the lake).

HISTORY OF THE SURVEY PROGRAM

The zooplankton preoperational cruises began in April 1969 and terminated in October 1974. Thirty-eight cruises were conducted. Zooplankton were collected at 7 to 46 stations each month and nearly 1,400 samples were examined. The operational cruises began in April 1975; the first cruise after Unit 1 went into operation in February 1975. Unit 2 went on line three years later in April 1978. Thirty-two cruises were conducted during the 1975-1978 period with each cruise consisting of 14 to 30 stations. Over 1,000 samples have been examined from this period. Over 50 species of copepods and cladocerans have been identified, with one or two new species occurrences noted in each of the more recent years of the study. At this point, a review of the sampling program is provided and the subsets of the data used in the statistical analyses specified.

The sampling grid, the collecting techniques, and the counting methods have improved over the years (Table 5). In the early years of the study, relatively few cruises were conducted but a large number of stations were sampled. Identifications, particularly for the cyclopoid copepods, were to a low level of taxonomic resolution. Since then, zooplankton have been identified to an increasingly higher level of taxonomic resolution. The mesh size of the nets used in collecting zooplankton, the number of replicate hauls made at each

Table 5. Summary of the field survey sampling program.

		Preoperational Years						Operational Years			
		69	70	71	72	73	74	75	76	77	78
Apr	Number of stations sampled	9		46	46	27	28	30	30	30	30
	Net mesh (μ)	282		158	158	158	158	158	158	158	158
	Replicates counted per stations	1		1	1	3	2	2	2	2	2
May	Number of stations sampled				8	7	14	14	30	14	14
	Net mesh (μ)				158	158	158	158	158	158	158
	Replicates counted per station				1	3	2	2	2	2	2
Jun	Number of stations sampled				8	158	14	14	14	14	14
	Net mesh (μ)				158	158	158	158	158	158	158
	Replicates counted per station				1	3	2	2	2	2	2
Jul	Number of stations sampled		46	46	28	27	30	30	30	30	30
	Net mesh (μ)		282	158	158	158	158	158	158	158	158
	Replicates counted per station		1	1	1	3	2	2	2	2	2
Aug	Number of stations sampled				7	7	14	30	14	14	14
	Net mesh (μ)				158	158	158	158	158	158	158
	Replicates counted per station				1	3	2	2	2	2	2
Sep	Number of stations sampled		46	46	7	7	14	14	14	14	14
	Net mesh (μ)		282	158	158	158	158	158	158	158	158
	Replicates counted per station		1	1	1	3	2	2	2	2	2

(continued).

Table 5. (continued).

		Preoperational Years						Operational Years			
		69	70	71	72	73	74	75	76	77	78
Oct	Number of stations sampled				27	27	30	27	26	30	30
	Net mesh (μ)				158	158	158	158	158	158	158
	Replicates counted per station				1	3	2	2	2	2	2
Nov	Number of stations sampled		46	46	7					14	14
	Net mesh (μ)		282	158	158					158	158
	Replicates counted per station		1	1	1					2	2
Dec	Number of stations sampled							14		14	
	Net mesh (μ)							158		158	
	Replicates counted per station							2		2	

station, and the subsampling techniques also have varied over the years. Since 1974, no substantial changes in methods have been made.

Stations

The number of stations sampled during a cruise has varied from a minimum of seven during the 1972 and 1973 short survey cruises to a maximum of 46 in the original (1970 to April 1972) major survey grid. Beginning in 1972, short surveys consisting of eight stations were initiated to provide supplemental information on zooplankton population dynamics. At this time, the major survey grid was reduced to 28 stations. Construction of the discharge structures

prevented sampling of DC-1 during most of 1972 and 1973. Dredging and construction of a temporary safe harbor during this time may have produced local changes in lake currents in what is now the thermal plume region. Since 1974, the number of major and short survey stations has remained unchanged at 30 and 14, respectively, except where noted in Table 5. Major surveys were conducted during some short survey months during the early part of the operational study. This occurred when the plant was not operational during the regularly scheduled major survey cruise. Poor weather and hazardous lake conditions prevented sampling at some of the offshore stations during two October cruises and prevented November cruises from being conducted in some years. Two supplementary December cruises were conducted during the operational period.

Only data collected during the April, July, and October major survey cruises (27 to 30 stations) were used in statistical analyses. Too few stations were sampled during the short survey cruises to justify statistical comparisons between the preoperational and operational periods. Data from both major surveys and short surveys were used to delineate zooplankton succession patterns and long-term trends in the plume region. However, too few stations were sampled in the northern and southern control areas during the short surveys to justify similar preoperational and operational comparisons.

Nets

A number 5 mesh net (282 μm) was used in 1969 and 1970, and a number 10 net (158 μm) was used in 1971 and continues to be used in the operational period. The 1969 and 1970 data were not used in the analyses because of the lack of comparability of these data with data collected using the finer mesh net.

Duplicate Samples

A single net haul was made at each station in 1971 and 1972. Since 1972, three replicate hauls were made at each station. However, only two of the three replicate samples generally were counted from 1974 to 1978. The third replicate occasionally was counted when there was an unusual discrepancy between abundance estimates of the first and second replicates.

Subsampling Techniques

Samples collected between 1969 and 1971 were subsampled with a Stempel pipette. Up to 15 1-mL subsamples were counted from each sample. A Folsom plankton splitter also was used to subsample some of the 1971 collections. Density estimates were comparable to those obtained with the pipette (Roth 1973). The Folsom plankton splitter has been used routinely since 1971. Methods of use are described in Section 1.

Taxonomic Identifications

The level to which zooplankton were identified has varied with the taxon, the year, and the station (Table 6). Most cladocerans were identified to genus beginning in 1970, although *Eubosmina* sp. and *Bosmina* sp. were enumerated as Bosminidae until 1972. Species identifications were made (as described in Section 1) at three stations (DC-2, DC-5, and DC-6) in 1972 and 1973 and at an increasing number of stations in 1974. Beginning in 1975, identifications have been to species at all 14 short survey stations and at 22 of the 30 major survey stations (Fig. 1). Zooplankton have been identified to species at all stations since 1977.

Table 6. Taxonomic resolution of zooplankton counts made between 1971 and 1978. Years in which taxa are counted at all stations (or at all "species" stations since 1973) are shown as solid lines, years in which taxa are counted at only a few stations (i.e., DC2, DC5 and DC6) are shown as dashed lines, and years in which taxa were not counted are blank.

Taxon	1971	1972	1973	1974	1975	1976	1977	1978
				Year				
Copepod nauplii	- -	- -	—	—	—	—	—	—
Cyclopoid C1-C6	—	—	—	—	—	—	—	—
Cyclopoid C1-C5	- -	- -	- - —	—	—	—	—	—
Cyclops spp. C1-C5			—	—	—	—	—	—
Tropocyclops sp. C1-C5			- -	- - —	—	—	—	—
Cyclopoid C6	- -	- -	—	—	—	—	—	—
Cyclops spp. C6	- -	- -	—	—	—	—	—	—
Cyclops bicuspidatus thomasi C6	- -	- -	- -	- - —	—	—	—	—
Cyclops vernalis C6	- -	- -	- -	- - —	—	—	—	—
Tropocyclops prasinus mexicanus C6	- -	- -	- -	- - —	—	—	—	—
all other cyclopoid species	- -	- -	- - —	—	—	—	—	—
Calanoid C1-C6	—	—	—	—	—	—	—	—
Calanoid C1-C5	—	—	—	—	—	—	—	—
Diaptomus spp. C1-C5			—	—	—	—	—	—
Epischura sp. C1-C5			—	—	—	—	—	—
Eurytemora sp. C1-C5			—	—	—	—	—	—
Limnocalanus sp. C1-C5			—	—	—	—	—	—
Calanoid C6	- -	- -	—	—	—	—	—	—
Diaptomus spp. C6	- -	- -	—	—	—	—	—	—
Diaptomus ashlandi C6	- -	- -	- -	- - —	—	—	—	—
Diaptomus minutus C6	- -	- -	- -	- - —	—	—	—	—
Diaptomus oregonensis C6	- -	- -	- -	- - —	—	—	—	—
Diaptomus sicilis C6	- -	- -	- -	- - —	—	—	—	—
Epischura lacustris C6	- -	- -	- - —	—	—	—	—	—
Eurytemora affinis C6	- -	- -	- - —	—	—	—	—	—
Limnocalanus macrurus C6	- -	- -	- - —	—	—	—	—	—
all other calanoid species	- -	- -	- - —	—	—	—	—	—
Harpacticoid C1-C6	—	—	—	—	—	—	—	—
Bryocamptus spp. C1-C5	—	—	—	—	—	—	—	—
Bryocamptus spp. C6	—	—	—	—	—	—	—	—
Canthocamptus spp. C1-C6	—	—	—	—	—	—	—	—
Canthocamptus spp. C6	—	—	—	—	—	—	—	—

(Continued).

Table 6. (continued).

Taxon	1971	1972	1973	1974	1975	1976	1977	1978
Cladocerans	—	—	—	—	—	—	—	—
Bosminidae	—	—	—	—	—	—	—	—
Bosmina longirostris	- -	- -	—	—	—	—	—	—
Eubosmina coregoni	- -	- -	—	—	—	—	—	—
Daphnia spp.	- -	- -	—	—	—	—	—	—
Daphnia retrocurva	- -	- -	- -	- -	—	—	—	—
Daphnia galeata mendotae	- -	- -	- -	- -	—	—	—	—
Daphnia longiremus	- -	- -	- -	- -	—	—	—	—
Alona spp.	—	—	—	—	—	—	—	—
Disparalona spp.*	—	—	—	—	—	—	—	—
Diaphanosoma spp.	—	—	—	—	—	—	—	—
Ceriodaphnia spp.	—	—	—	—	—	—	—	—
all other cladoceran species	—	—	—	—	—	—	—	—
Asplanchna spp.	—	—	—	—	—	—	—	—

*Designated *Alonella* spp. before 1976

Adult calanoid copepods and cladocerans were identified to genus at most preoperational stations and to species at most operational stations. Copepods also were sexed, although this information has not yet been fully analyzed and will be discussed in a later report. Immature calanoid copepodites were combined as a group until 1973. Since then they have been identified to genus.

Cyclopoid copepods generally were combined as a group until 1973, although immatures and adults were distinguished at three species stations (DC-2, DC-5, and DC-6) beginning in 1972. Since April 1973, adult *Cyclops* spp. have been separated from immatures at all stations. *Tropocyclops* sp. adults and immature copepodites were not distinguished until 1974. Nor were immature and adult harpacticoid copepods distinguished until 1974. Beginning in 1974, cyclopoid

and harpacticoid copepods were identified to the same level of taxonomic resolution as calanoid copepods.

Nauplii were combined into a single category. They were not enumerated in 1969 and 1970 when the 282 μm mesh net was used. A 158 μm net has been used since 1971. However, nauplii densities are underestimated as many of the smaller cyclopoid nauplii escape through this even finer mesh net (Sell and Evans 1981). Studies utilizing collections made in 1979 with a 76-μm mesh net suggest that this loss may exceed 50%. Nauplii were not routinely counted at all stations until 1972.

The only rotifer enumerated was *Asplanchna* spp. Although other rotifer species occurred in the samples, their small size precluded their being sampled quantitatively by the 158-μm aperture net.

METHODS

Analytical Design of the Survey Grid

Examinations of the preoperational and operational data have shown that zooplankton vary in abundance over the survey grid and that the greatest differences are associated with depth or distance from shore (Section 1; Evans *et al*. 1980). Our subdivision of the survey grid into four depth-related regions (Fig. 34) is supported by the results of principal component analyses and graphical analyses of zooplankton density-depth trends. These regions are designated the inshore (5- to 10-m depth contour), the middle (10- to 20-m depth contour), the inner offshore (20- to 30-m depth contour), and the outer offshore (>30-m depth contour) regions.

Although zooplankton varied in abundance along transects parallel to shore, this variation was not consistent from month to month and was probably

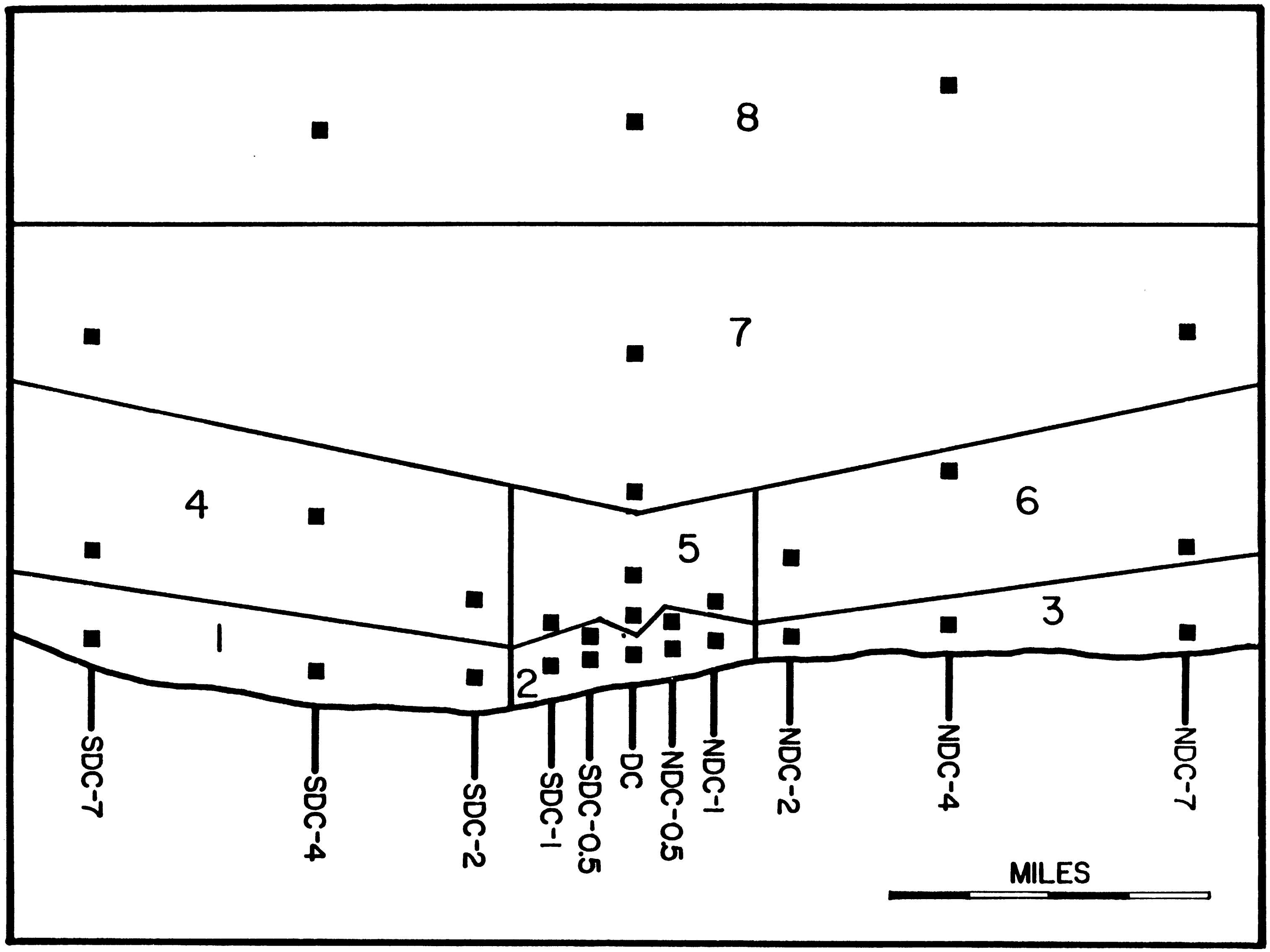

FIG. 34. Thirty station major survey grid divided into the eight zones used in the preoperational and operational comparisons.

associated with transient zooplankton patchiness. We could not further subdivide the survey grid on the basis of consistently observed alongshore patterns in zooplankton abundance. Further subdivisions were based on the location of the thermally detectable plume. Generally, the plume was detected only within 1.6 km of the discharge jets (DC-1) and, while it generally flowed parallel to shore, it sometimes had a strong offshore component (Section 1; Indiana & Michigan Electric Company 1976). The inshore and middle depth regions were subdivided into plume zones extending 1.6 km north and south of the discharge site, and into northern and southern control zones. The small number of stations in the two offshore zones precluded further subdivision of these areas (Fig. 34).

Temporal succession patterns of selected taxa in the inshore plume zone (Zone 2) were examined in time series graphs. These graphs facilitate examination of zooplankton temporal succession patterns for evidence of long term population trends. These graphs also provide information on the magnitude of temporal variations in zooplankton abundance both from month to month and from year to year.

Statistical analyses comparing zooplankton abundances between the preoperational and operational periods were the major tests used in evaluating plant effects. These analyses utilized the major survey data and compared zooplankton abundances by zone and by month between the preoperational and operational periods.

Statistical Test Design

The data set was stratified into preoperational and operational blocks, and station density estimates were compared by using the Mann-Whitney U test (Siegel

1956, Conover 1971). These comparisons were made separately for each month and zone in order to reduce spatial and temporal variability which was irrelevant to our investigation of power plant impact. The Mann-Whitney U test is a non-parametric procedure based on the ordered ranks of the data. A two-sided test was used to evaluate the zone densities before and during plant operation. The power efficiency of the Mann-Whitney U test is at least 86% that of the parametric t-tests and is generally higher when the data are not normally distributed (Conover 1971).

The assumptions underlying the Mann-Whitney U tests appear to have been met. The samples were independent and drawn randomly from the zooplankton populations at each station. The density estimates represented continuous random variables and the measurement scale was at least ordinal. The third assumption is that control and experimental populations differed only in the location of their mean.

Parametric tests for detecting differences between populations, such as Student's t-tests and the analysis of variance, were not used. Their assumption of normality could not be met by all the data. Both log ($\#/m^3$ + 1) and square root transformation of the density estimate failed in most cases to result in normality.

Calculations were performed on the AMDAHL 470V/6 computer at The University of Michigan using the TWOSAMPLE program incorporated into MIDAS. Zone densities differing at the 95% confidence level were considered statistically significant. Monthly zone densities were calculated for each taxon in the preoperational and operational period.

Zooplankton Taxa Tested

Although over 50 species of zooplankton taxa have been identified in the survey area, it was neither practical nor necessary to analyze the distributions of all taxa. We used the guidelines set by the Michigan Department of Natural Resources in selecting taxa to be considered in the evaluation of plant operation effects on the "maintainance of a balanced indigenous population in the discharge area." The department recommended that the following categories of zooplankton be considered for preoperational and operational comparisons:

(1) those taxa which account for 10% of the zooplankton by weight or by numbers in each of the four seasons

(2) threatened or unique species

(3) pollution-tolerant species

(4) temperature-sensitive species

(5) nuisance-potential species

(6) species of significance to public health

(7) species indicative of certain water quality or environmental conditions

(8) species of historical significance.

They further recommended that all life forms be evaluated (adults, juveniles, growth, feeding, etc.)

The numerically dominant species in the spring, summer, autumn, and winter have been identified (Section 1) as _Cyclops_ spp., _Bosmina longirostris_, _Eubosmina coregoni_, and _Daphnia_ spp. Potentially pollution tolerant species include _Cyclops bicuspidatus thomasi_ and _Bosmina longirostris_ (Gannon and Stemberger 1978). A number of other species thrive in shallow, eutrophic waters (_C. vernalis_, _Eurycercus lamellatus_, _Alona_ spp., and _Chydorus sphaericus_).

However, they generally are rare in the plankton in the survey area (Table 4). The error associated with estimating concentrations of these taxa is so large that only extremely large differences in abundances could be detected with the four-year operational data base. Visual comparisons of these preoperational and operational data did not reveal such differences, so the data were not subject to further analyses.

Temperature sensitive zooplankton include *Limnocalanus macrurus*, *Daphnia longiremis*, and *Diaptomus sicilis*. Statistical analyses were performed only for *L. macrurus* in April: this taxon was not sufficiently abundant over the survey grid in July and October to merit further statistical analyses. The preoperational data base was not adequate for *D. longiremis* and *D. sicilis* as these taxa were identified to species at only a limited number of stations.

All zooplankton are important in energy transfer, although it is not possible to quantify the importance of each species. The numerically dominant herbivores (*Diaptomus* spp., *Bosmina* sp., *Daphnia* spp.) were used in the analyses but the rarer copepods and cladocerans were not. The only omnivores sufficiently abundant for statistical analyses were *Limnocalanus macrurus* and *Cyclops* species. Carnivorous zooplankton such as *Polyphemus pediculus*, *Leptodora kindtii*, and adult *Epischura lacustris* were not sufficiently abundant to merit statistical analysis. *Asplanchna* spp., a carnivorous rotifer, was occasionally abundant, and preoperational and operational comparisons were made for this genus in selected months.

There are no zooplankton in categories 2, 5, 6, and 8. The monitoring program was not designed to measure zooplankton physiological processes such as feeding and growth. Some information on growth is available for the copepods as three developmental categories (nauplii, immature copepodites, and adults) are considered.

Comparisons were made at several taxonomic levels. Order and suborder classifications (i.e., Cladocera, Cyclopoida, Calanoida) were used in order to utilize the largest possible preoperational data set (1971-1974) for making preoperational and operational comparisons. Comparisons at the genus or species level and for immature and adult copepodites could be made only with a two- or three-year subset of the preoperational data base.

RESULTS

Temporal Abundance Patterns of Zooplankton in Zones 2, 5, 7, and 8 (1971-1978)

The temporal abundance patterns of the 10 most common zooplankton taxa in Zones 2 (inner plume zone), 5 (outer plume zone), 7 (inner offshore zone), and 8 (outer offshore zone) were examined to determine the major features of their seasonal cycles. In Zones 2 and 5, these patterns were compared in the preoperational and operational periods to investigate whether or not power plant operation had any apparent effect on zooplankton temporal succession and population trends in the vicinity of the plume (Figs. 35 and 36). Similar plots for Zones 7 and 8 provide information on temporal succession in the offshore region of southeastern Lake Michigan (Figs. 37 and 38).

Overall, in Zones 2 and 5, temporal succession patterns were similar in the operational and preoperational periods (Figs. 35 and 36). For the most part, the range of population densities observed in the preoperational period was not exceeded in the operational period. Exceptions were adult *Diaptomus* spp., *Eurytemora affinis* C1-C6, and *Eubosmina coregoni* whose maximum attained abundances in the operational period were 1.5 to 5 times those attained in the preoperational period. *Eurytemora affinis* and *Eubosmina coregoni* also attained greater abundances in Zone 7 (Fig. 37) in the operational period than in the

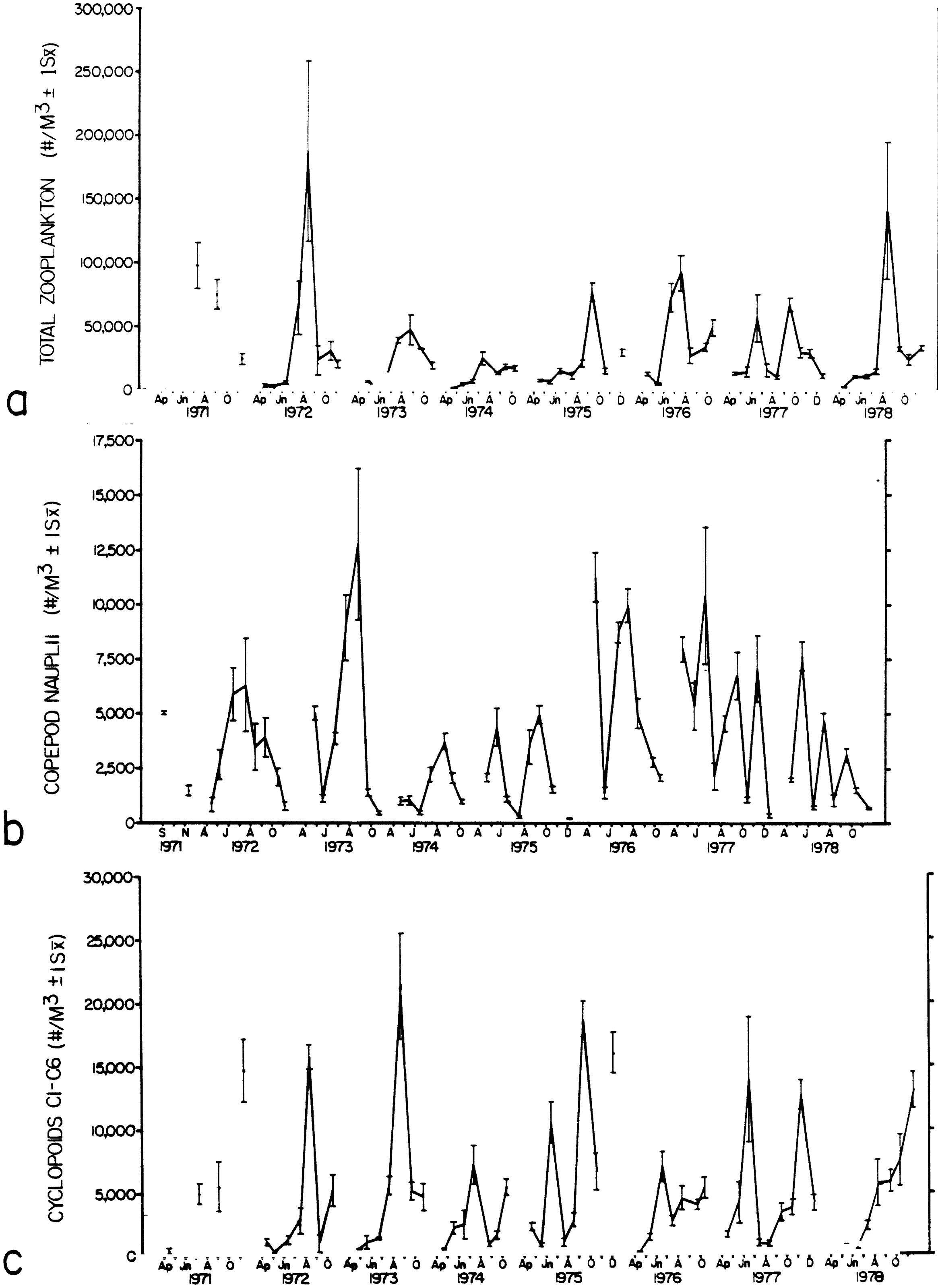

FIG. 35. The monthly abundance of zooplankton in the inshore plume zone (Zone 2) between 1970 and 1978. a) Total zooplankton, b) copepod nauplii, c) cyclopoid copepods C1–C6,

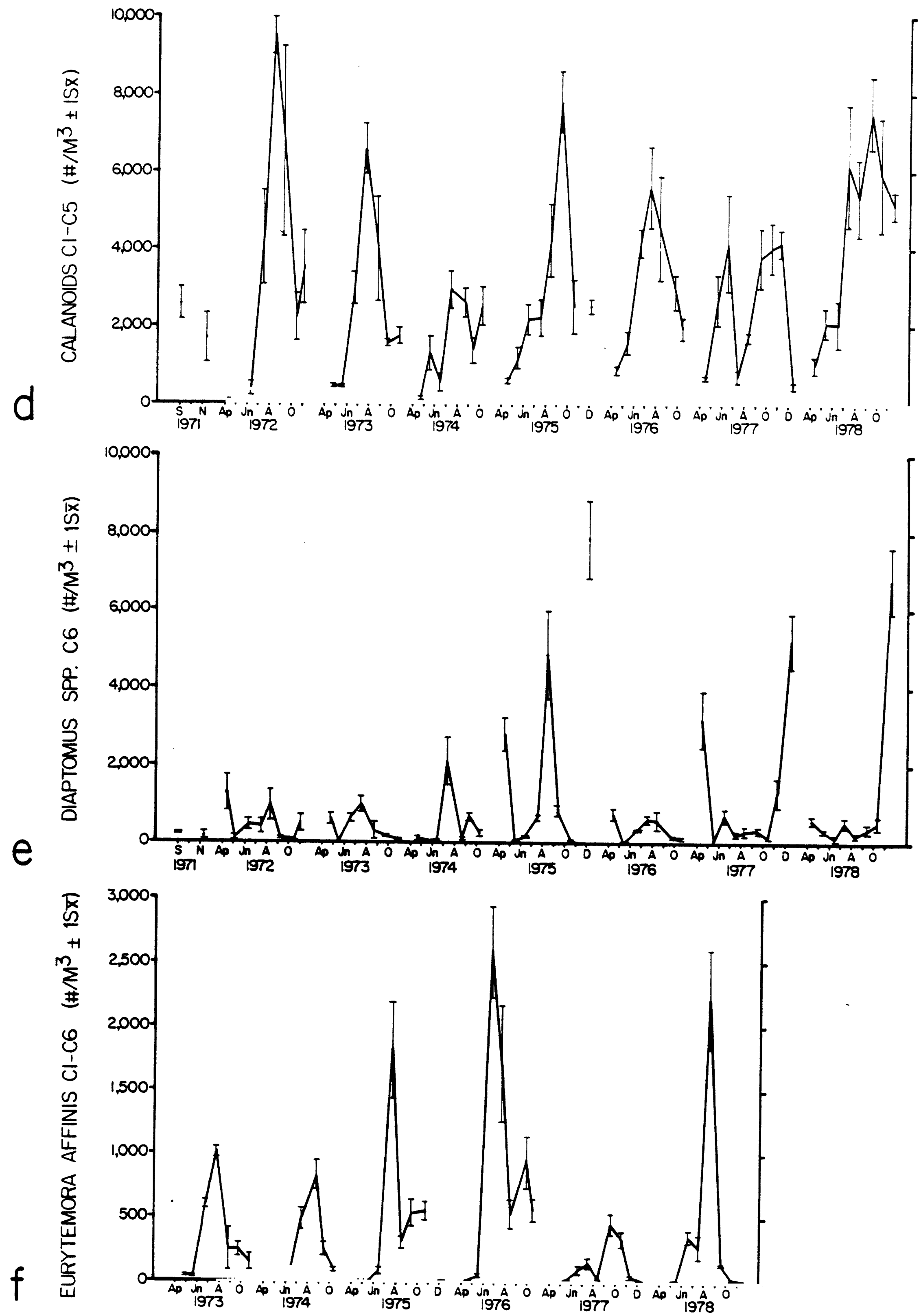

FIG. 35. Continued. d) calanoid copepods C1-C5, e) *Diaptomus* spp. C6, f) *Eurytemora affinis* C1-C6,

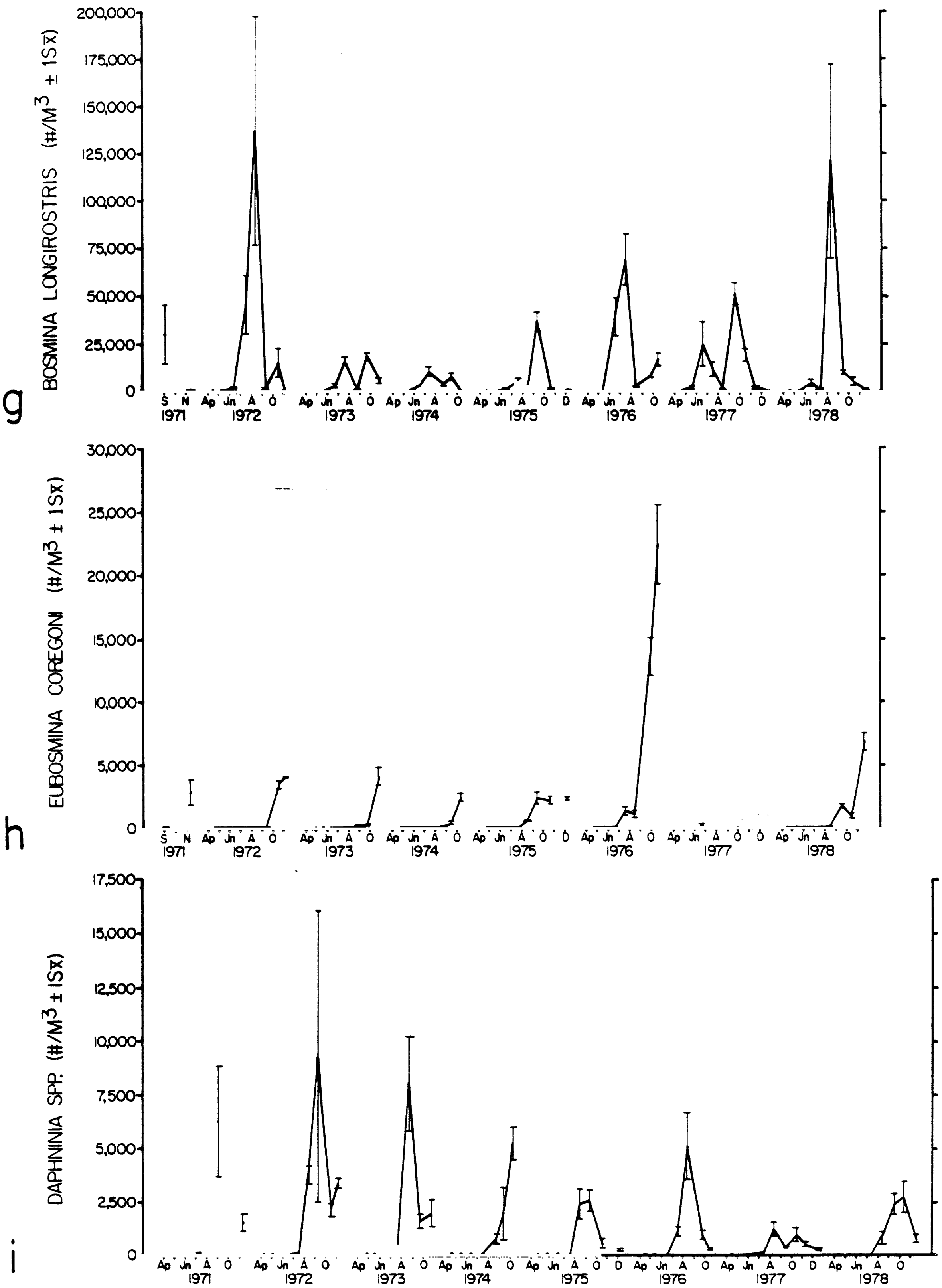

FIG. 35. Continued. g) Bosmina longirostris, h) Eubosmina coregoni, i) Daphnia spp.,

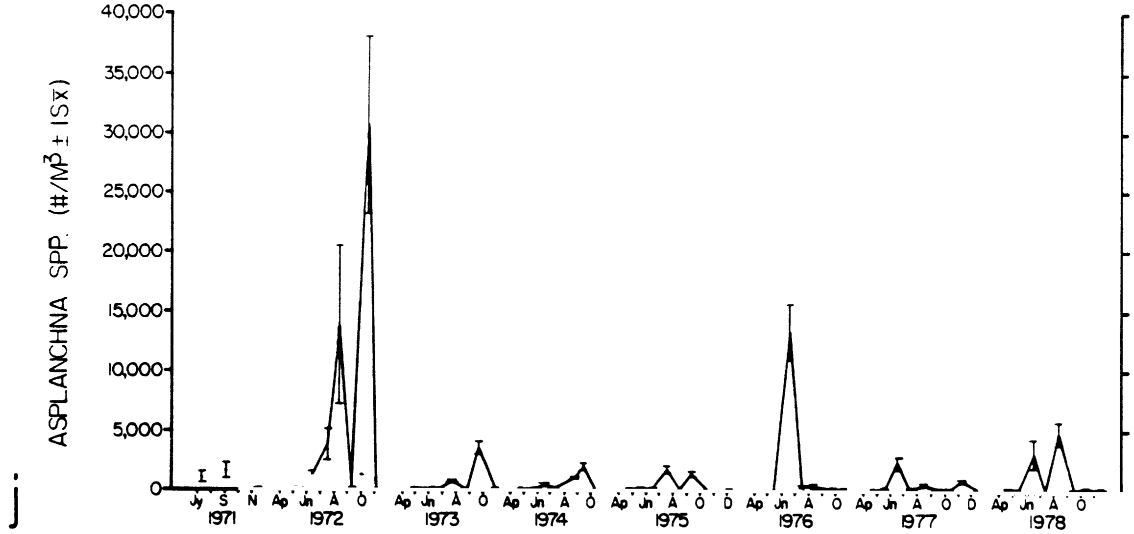

FIG. 35. Concluded. j) Asplanchna spp.

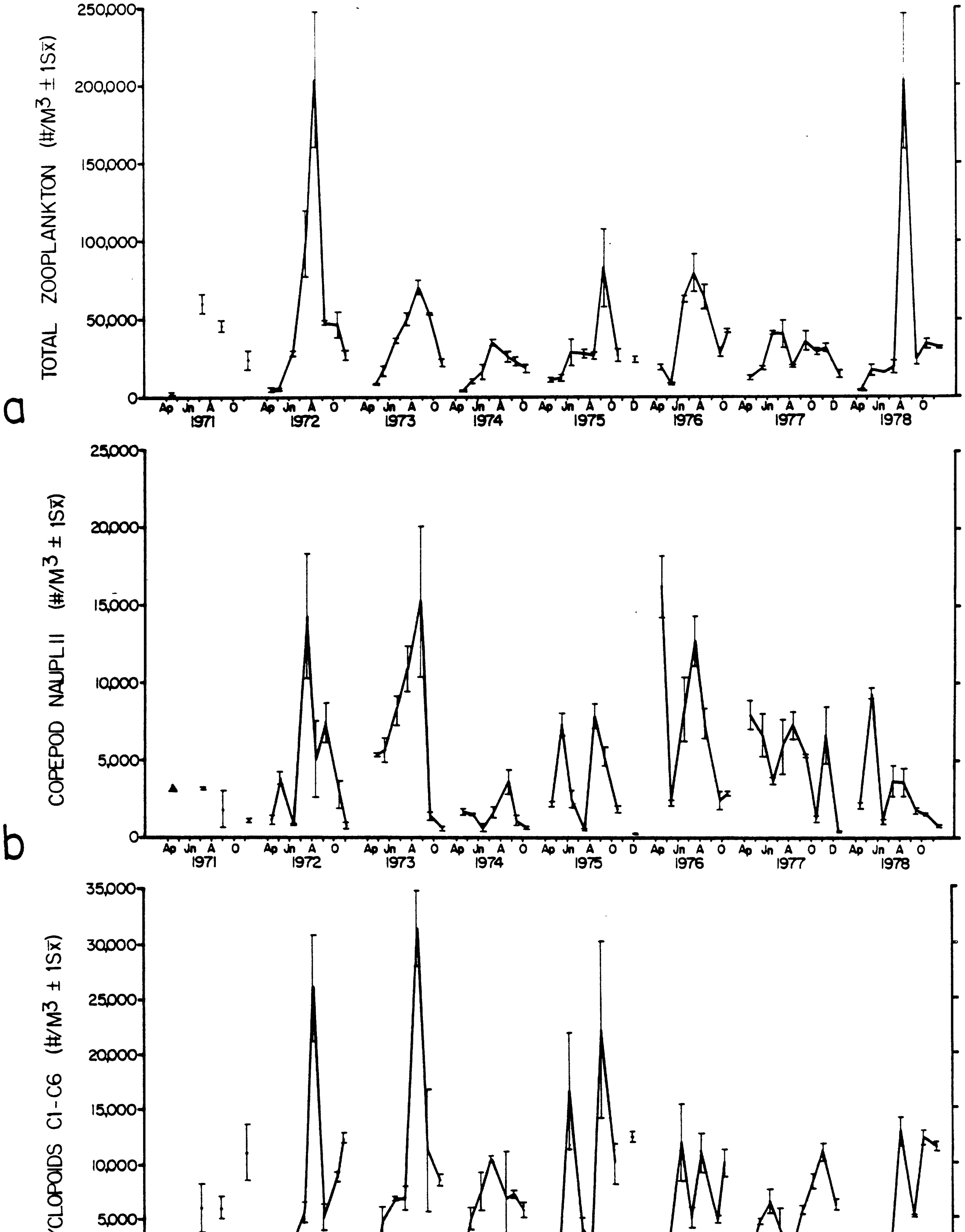

FIG. 36. The monthly abundance of zooplankton in the middle shore zone (Zone 5) between 1970 and 1978. a) Total zooplankton, b) copepod nauplii, c) cyclopoid copepods C1-C6,

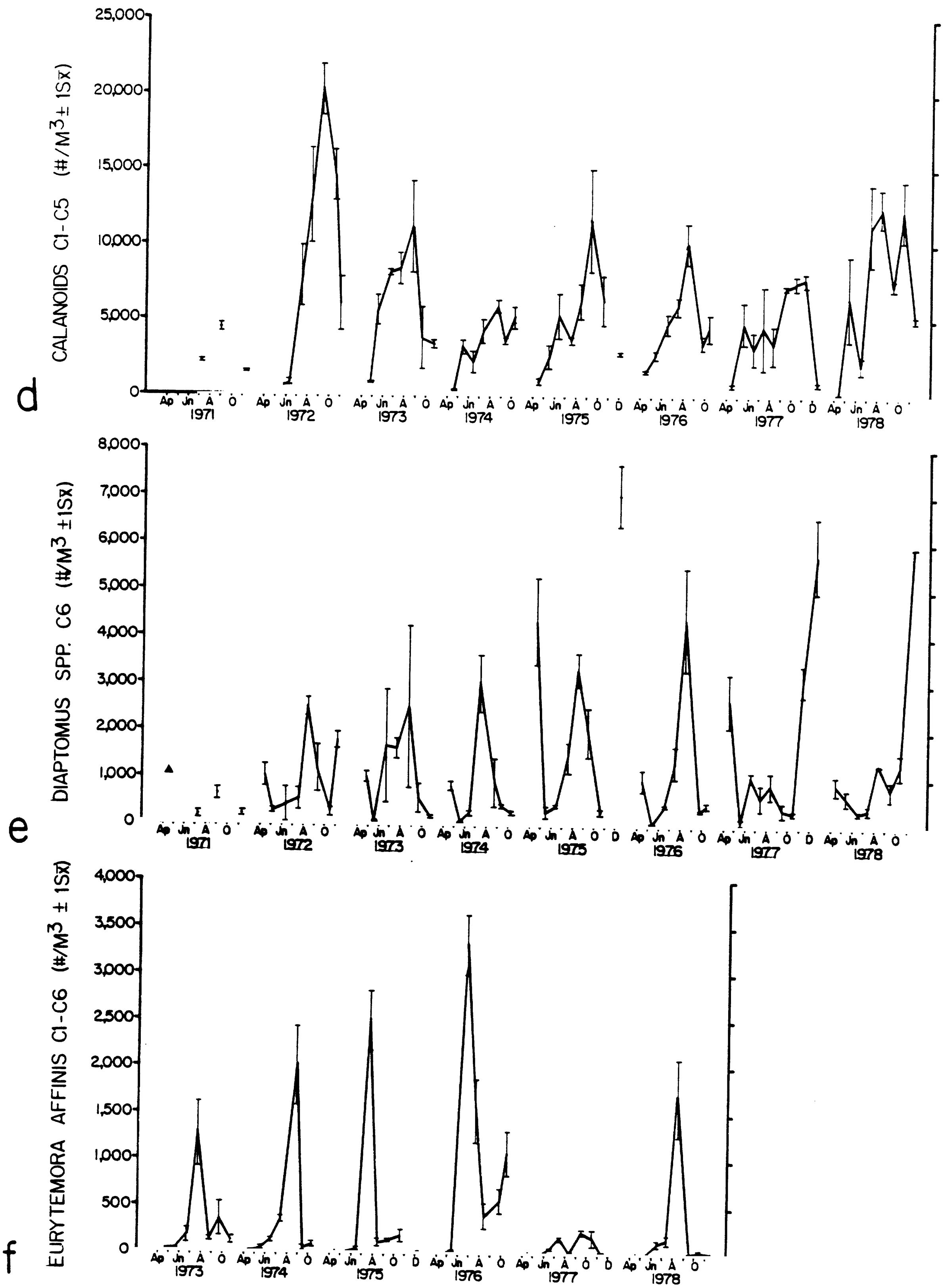

FIG. 36. Continued. d) calanoid copepods C1–C5, e) Diaptomus spp. C6, f) Eurytemora affinis C1–C6,

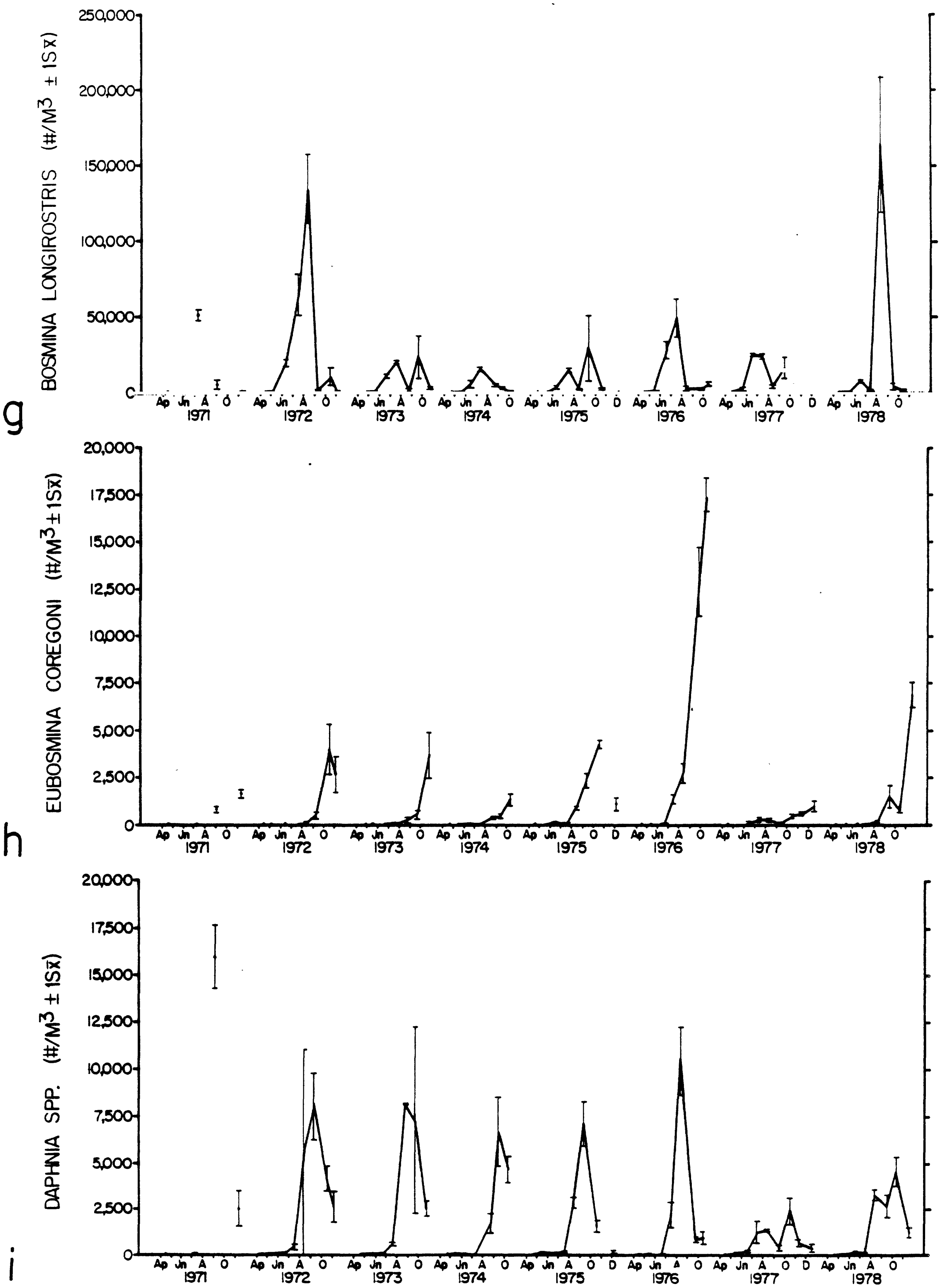

FIG. 36. Continued. g) Bosmina longirostris, h) Eubosmina coregoni, i) Daphnia spp.,

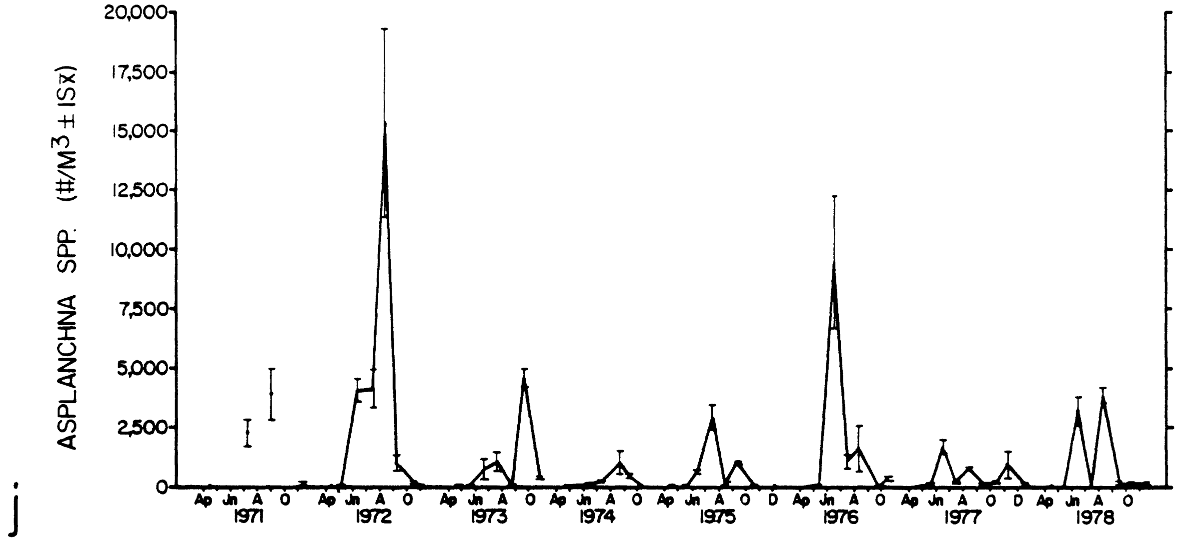

FIG. 36. Concluded. j) Asplanchna spp.

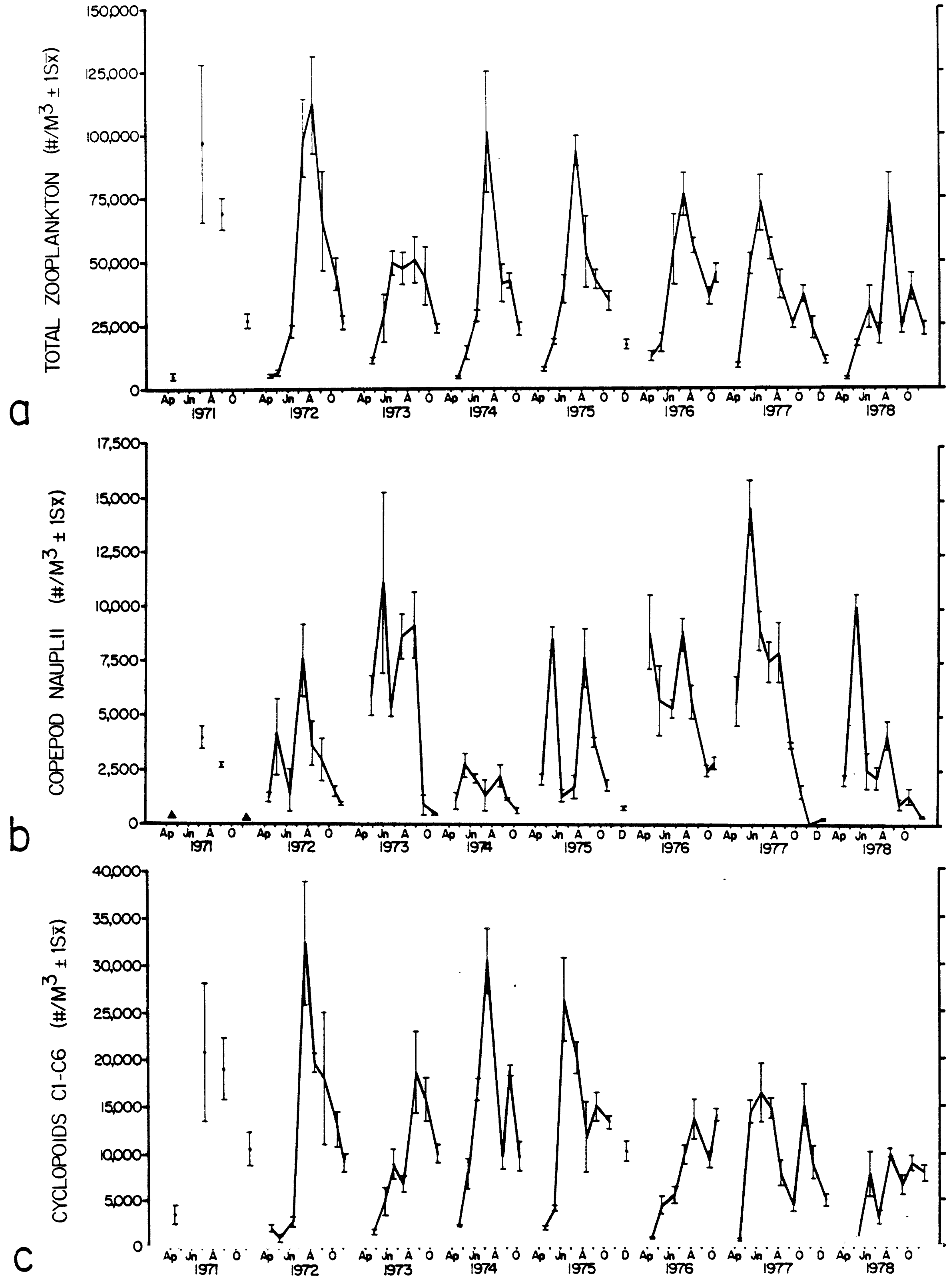

FIG. 37. The monthly abundance of zooplankton in the inner offshore zone (Zone 7) between 1970 and 1978. a) Total zooplankton, b) copepod nauplii, c) cyclopoid copepods C1-C6,

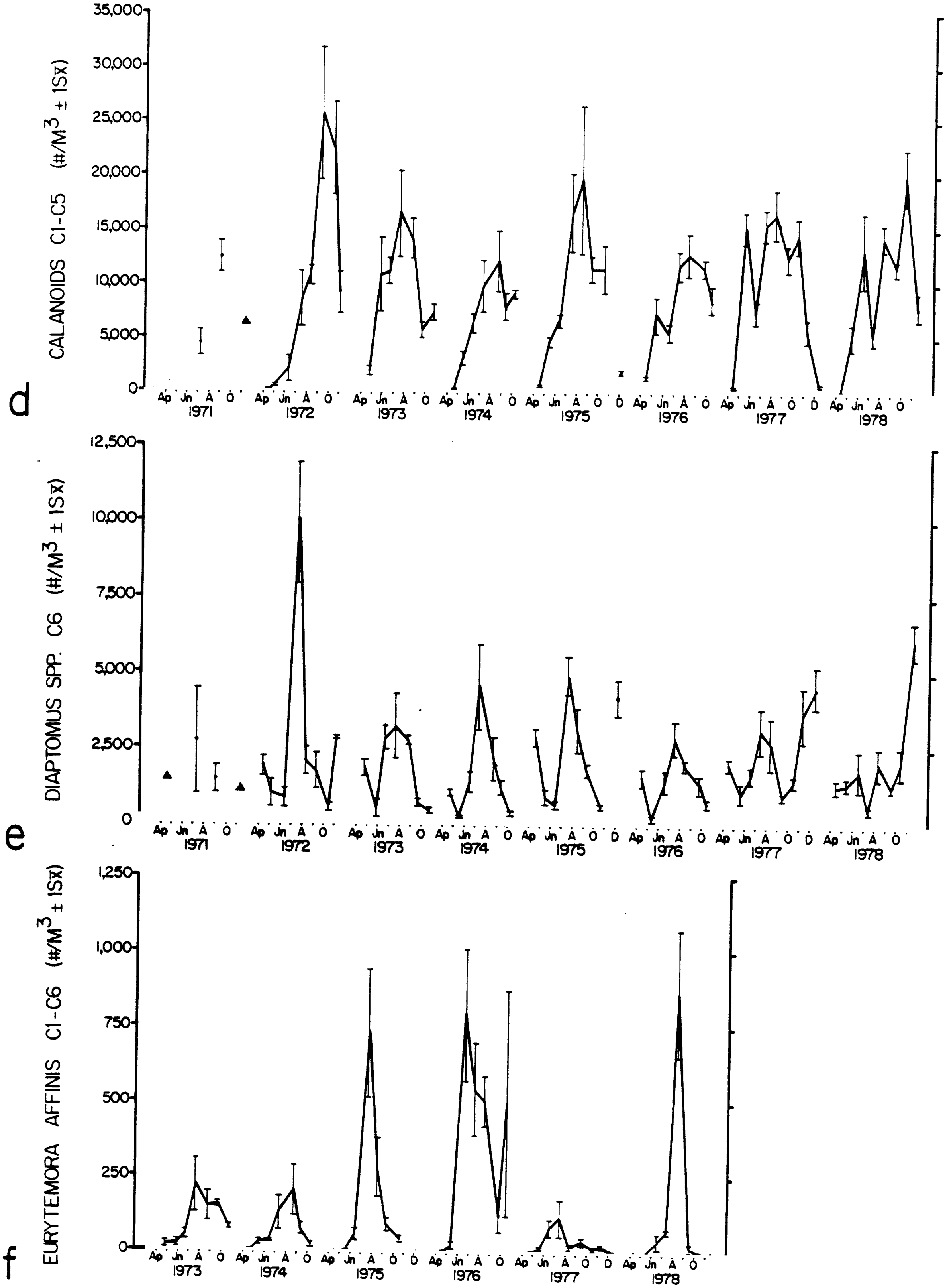

FIG. 37. Continued. d) calanoid copepods C1-C5, e) <u>Diaptomus</u> spp. C6, f) <u>Eurytemora affinis</u> C1-C6,

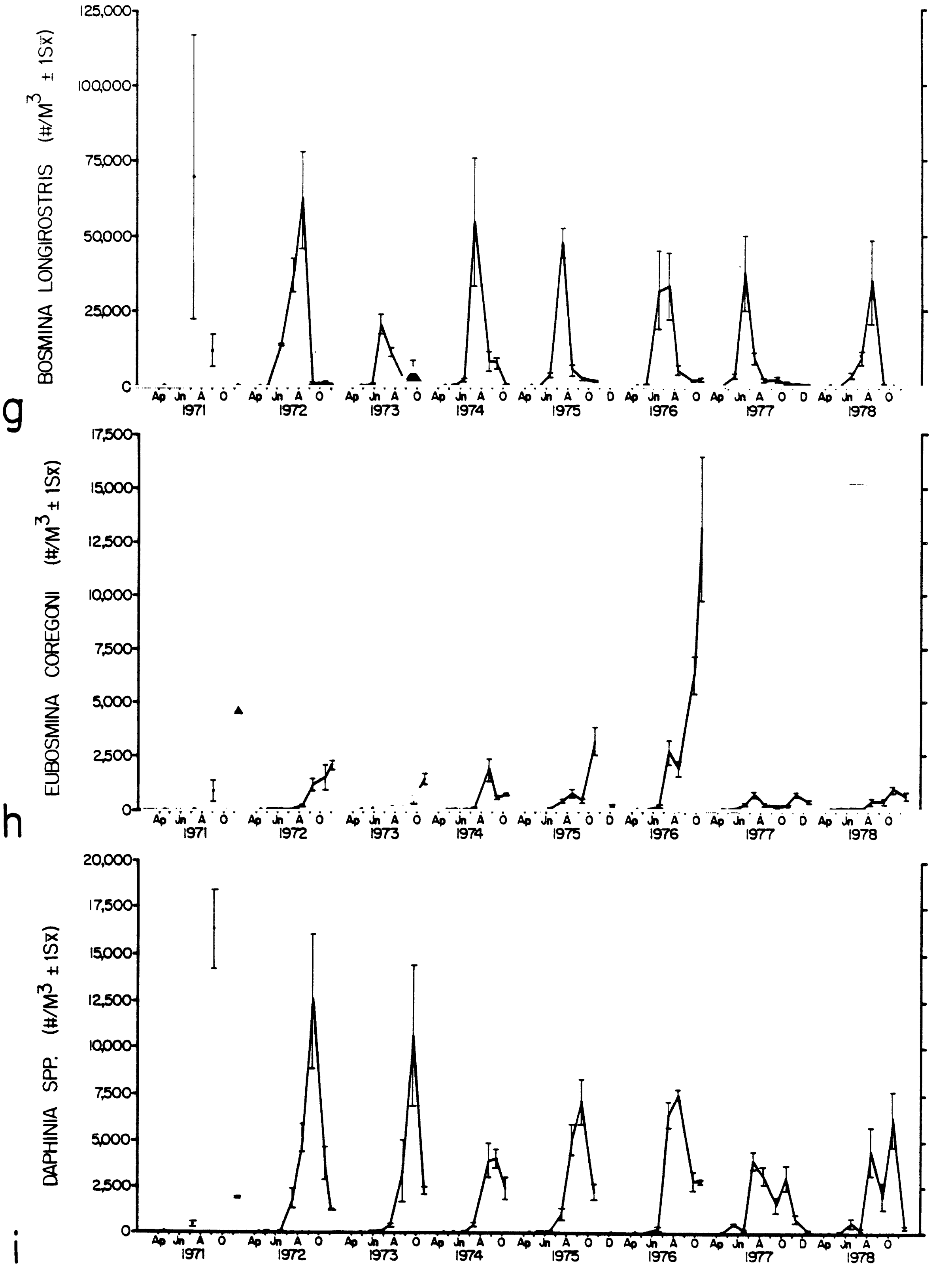

FIG. 37. Continued. g) Bosmina longirostris, h) Eubosmina coregoni, i) Daphnia spp.,

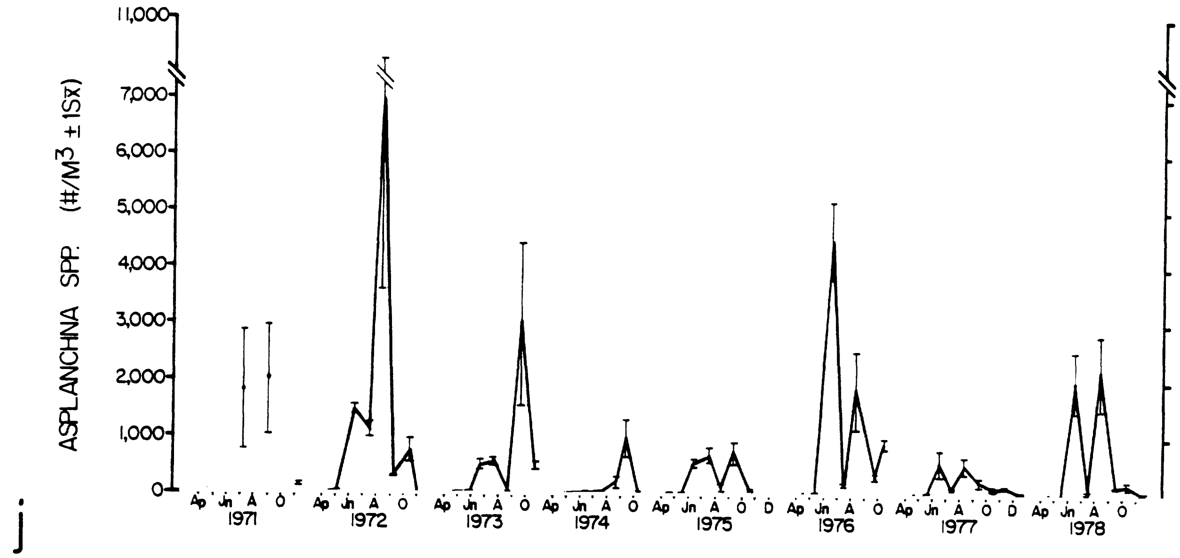

FIG. 37. Concluded. j) Asplanchna spp.

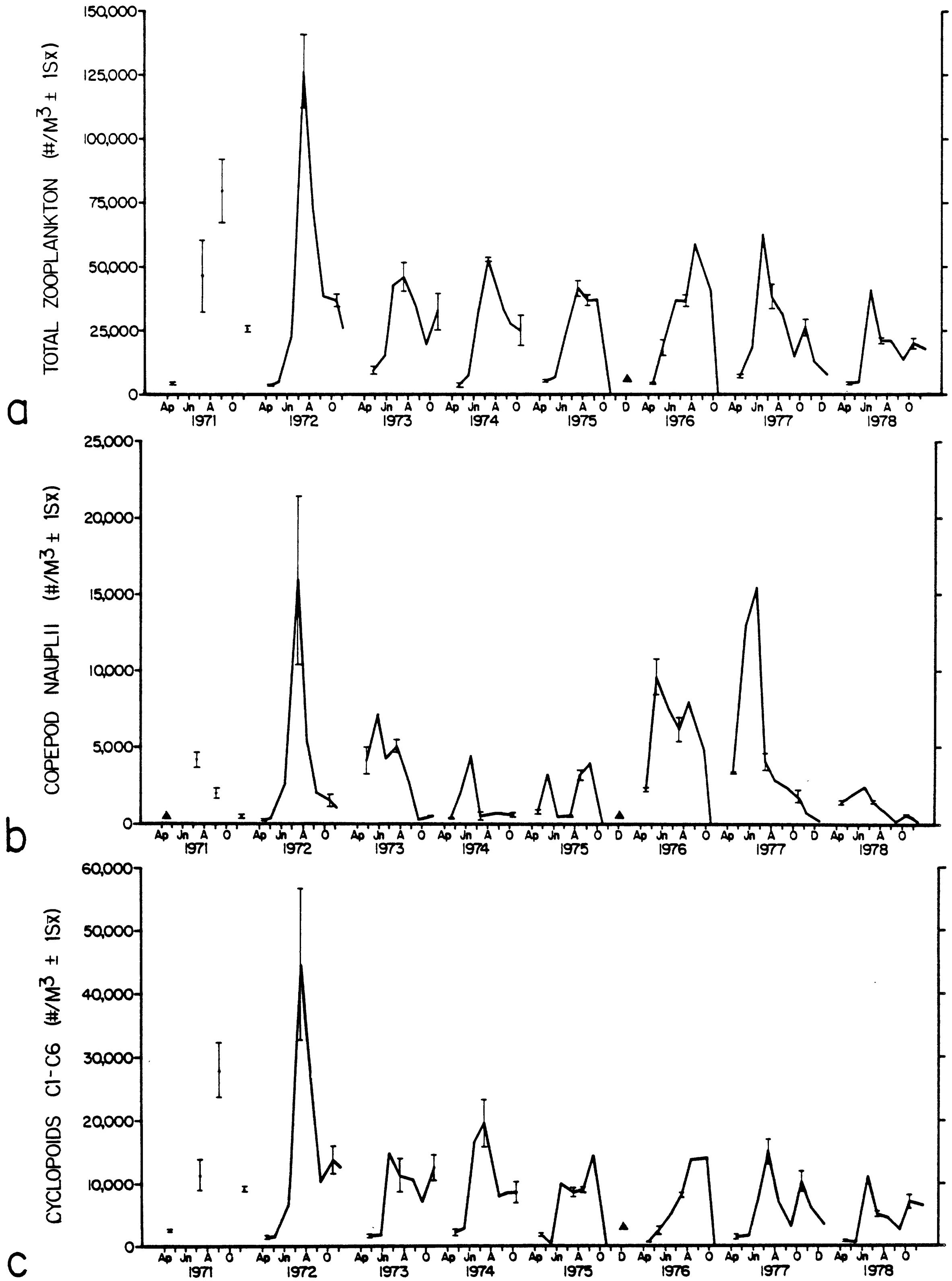

FIG. 38. The monthly abundance of zooplankton in the outer offshore zone (Zone 8) between 1970 and 1978. a) Total zooplankton, b) copepod nauplii, c) cyclopoid copepods C1-C6,

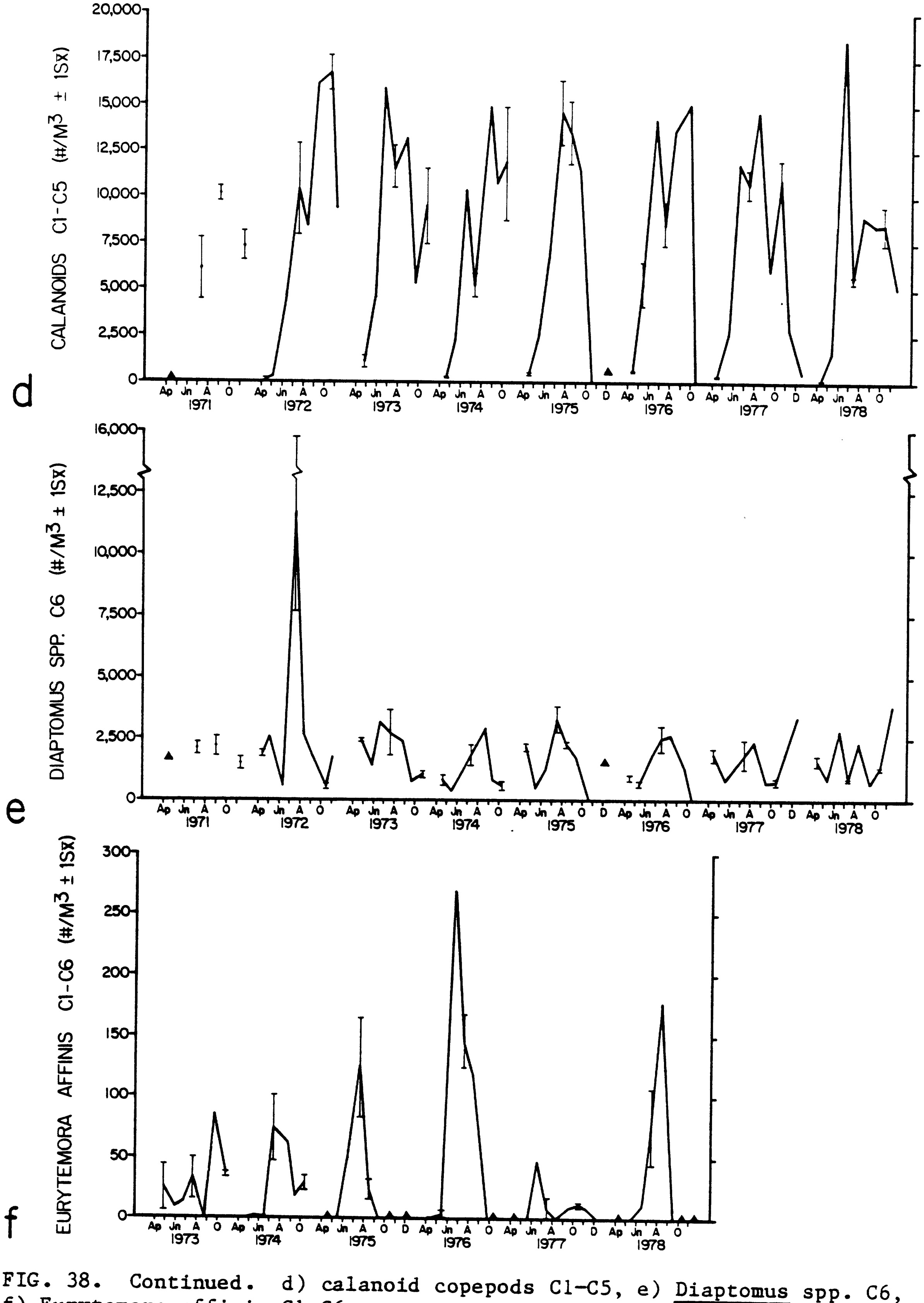

FIG. 38. Continued. d) calanoid copepods C1–C5, e) Diaptomus spp. C6, f) Eurytemora affinis C1–C6,

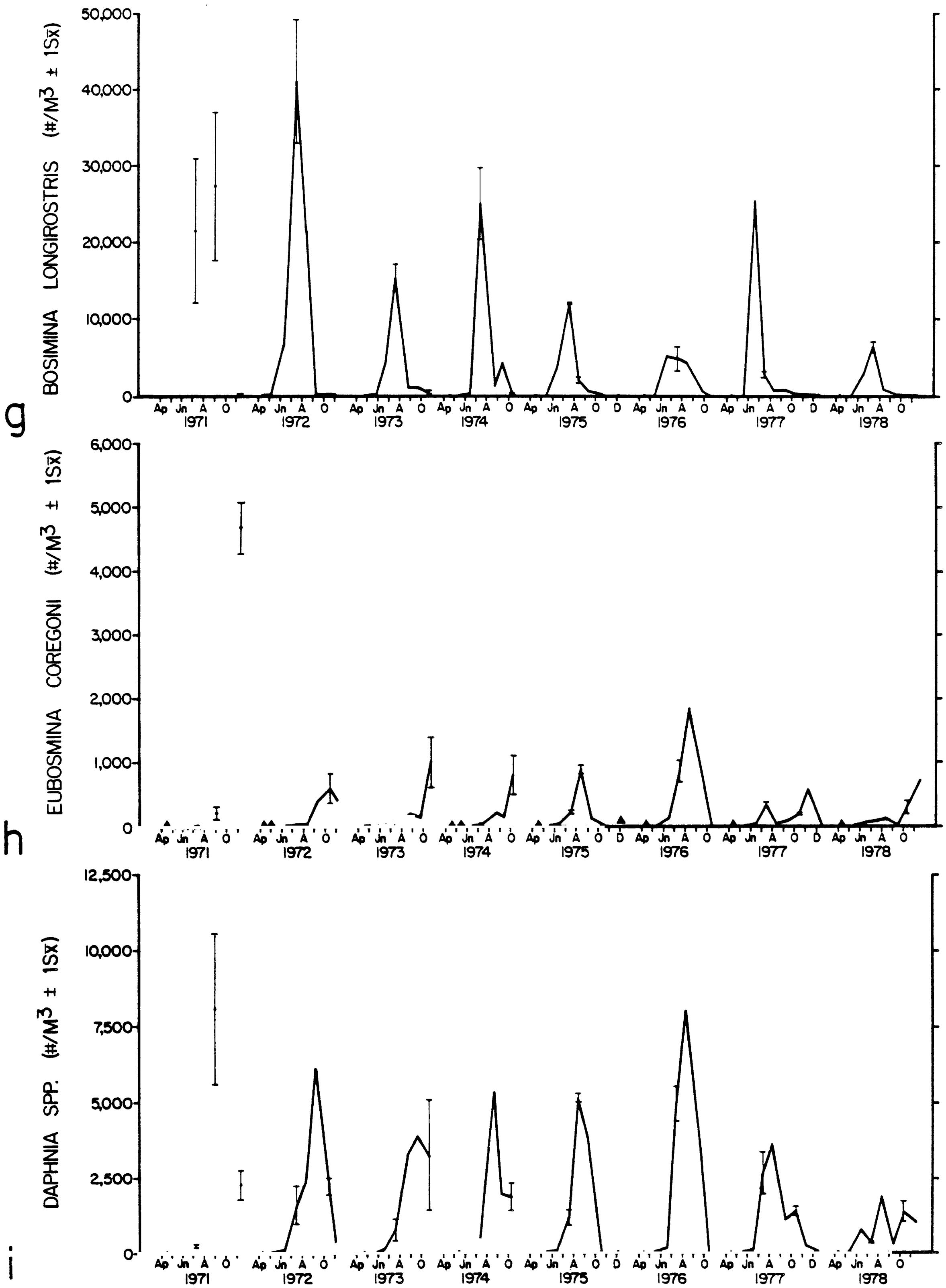

FIG. 38. Continued. g) Bosmina longirostris, h) Eubosmina coregoni, i) Daphnia spp.,

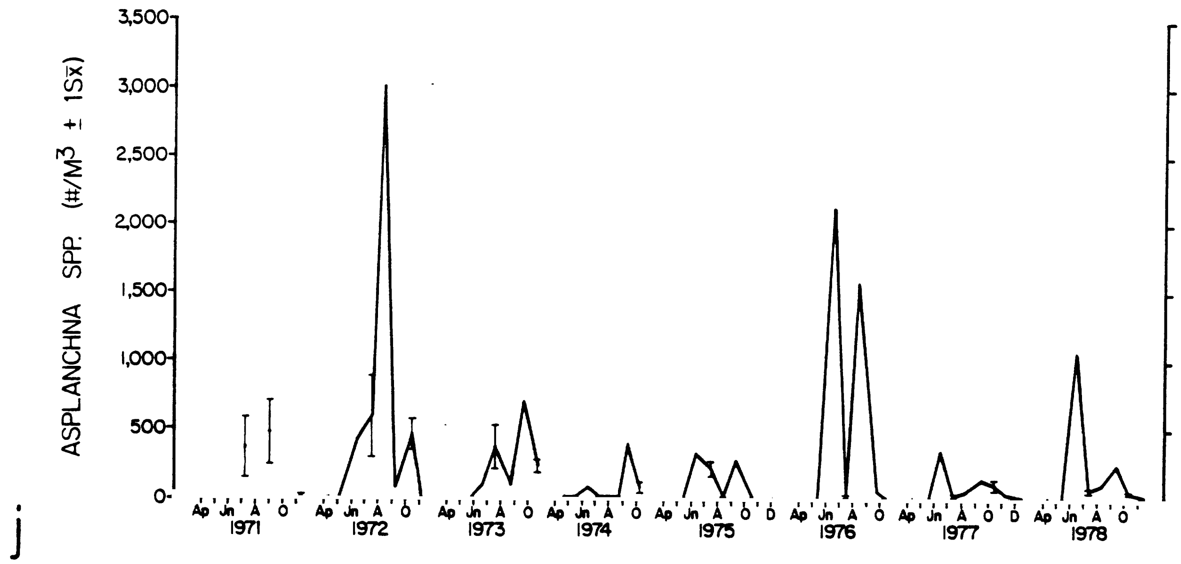

FIG. 38. Concluded. j) Asplanchna spp.

preoperational period. This suggests that peak abundances of E. affinis and E. coregoni in the operational period were related to a widespread event occurring in the southeastern basin of Lake Michigan. High operational abundances of Diaptomus spp. in Zone 2 occurred in April and August 1975, April 1977, and November 1978 and, in Zone 5, in April 1975 and November 1978. December cruises were not conducted in the preoperational period, so it is not possible to evaluate the significance of the high zooplankton densities in December 1975 and 1977. High April abundances are discussed below in the statistical analysis of preoperational and operational cruises.

Temporal succession patterns were similar in the preoperational and operational periods. Zooplankton occurred in low numbers in spring and increased in abundance through summer. Often a mid-summer decline in numbers was followed by an autumn pulse. Nauplii, immature calanoid and cyclopoid copepodites, and adult Diaptomus species occurred in relatively low numbers in spring with maximum population size attained in summer or autumn. Bosmina longirostris, a summer-autumn cladoceran, occurred in similar preoperational and operational temporal succession patterns. It did not appear earlier in the plankton nor persist for longer periods of time after the plant became operational. In the preoperational period, Daphnia spp. occurred in maximum numbers primarily in the late summer and autumn: this continued to be observed in the operational period. In Zone 2, Eubosmina coregoni did not increase markedly in abundance until late September-early October in the preoperational period. After the plant became operational, E. coregoni tended to occur in somewhat greater numbers in Zone 2 in mid-summer than observed in the preoperational period. However, this also was observed in Zone 7, suggesting that the earlier summer increase in E. coregoni was not directly related to plant operation.

Statistical Comparisons of April Preoperational and Operational Abundances

The preoperational and operational abundances in April for nine zooplankton taxa were compared using the Mann-Whitney U test. *Diaptomus* spp. immature copepodites was the only taxon which did not exhibit significantly ($p < 0.05$) different concentrations between the April preoperational and operational periods (Table 7). Significant differences were detected not only in the inshore and middle plume zones (Zones 2 and 5) but also in the southern and northern control zones (Zones 1, 3, 4, and 6) and the inner and outer offshore zones (Zones 7 and 8). Nauplii, *Limnocalanus macrurus* copepodites, calanoid copepodites, and total zooplankton all occurred in statistically significant higher operational concentrations in most, or all, of the inshore zones. The remaining taxa exhibited significantly different abundances between time periods, but showed less consistent spatial patterns in changes of abundances.

Nauplii (Fig. 39) was the numerically dominant taxon over most of the survey grid and occurred in higher concentrations (by a factor of 2 to 4) in the operational years (except for Zone 8) than in the preoperational period at statistically significant levels. High concentrations of nauplii in April 1976 and 1977 were the major reason for the increased operational mean zone concentrations. Nauplii concentrations were lower in April 1975 and 1978 and were comparable to abundances in the preoperational period.

Cyclopoid copepodites (Fig. 39) had statistically similar preoperational and operational densities in all zones except the two offshore zones, where the mean operational densities were lower. Adult *Cyclops* spp. had higher densities by factors of 1.5 to 8 in the six inshore and middle zones, but the only statistically significant difference was in the inner offshore zone where the mean operational density was lower. Immature cyclopoid copepodites had

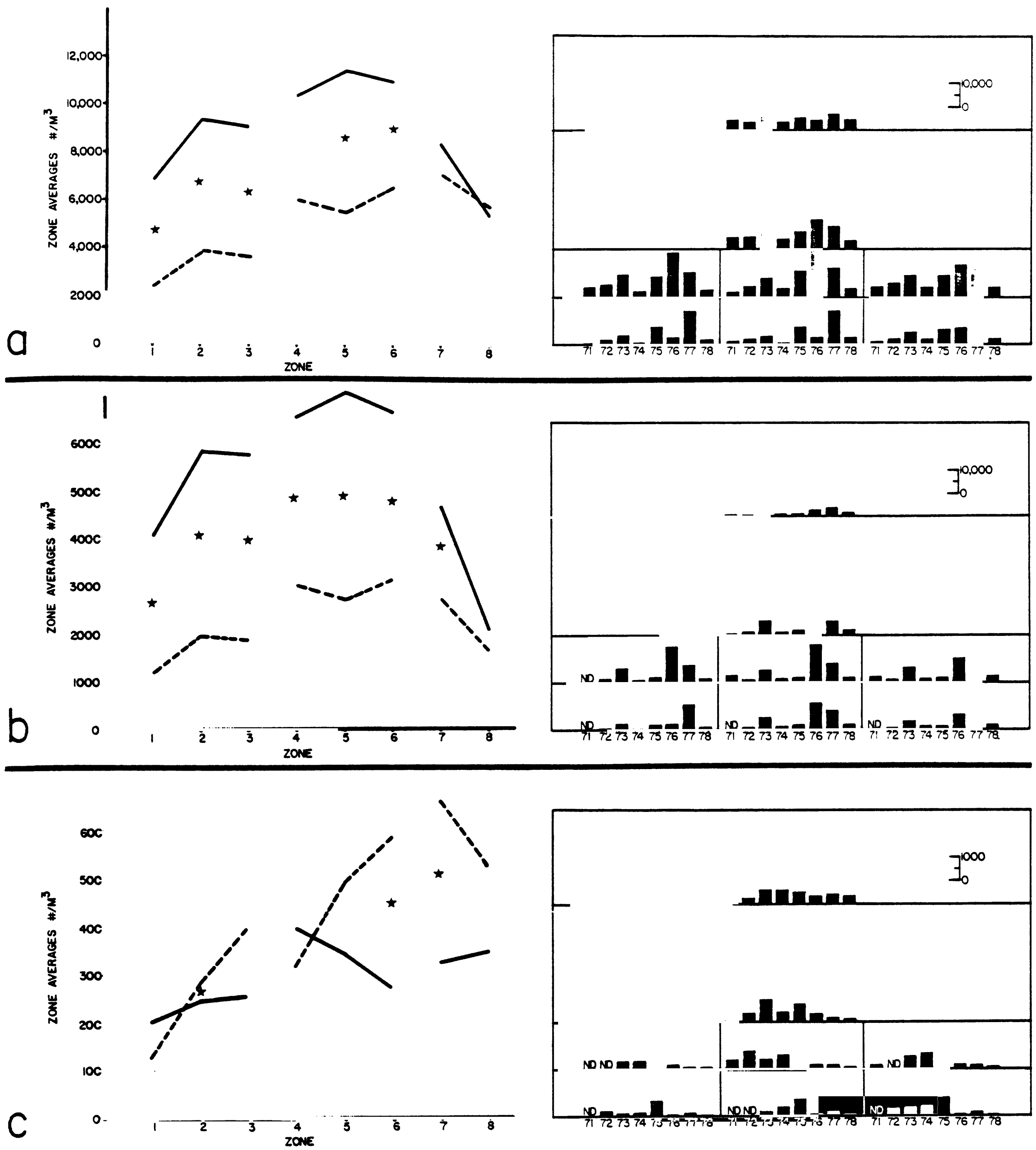

FIG. 39. The mean densities of zooplankton taxa in April of each year, 1971-1978, are given in the histograms. The mean preoperational and operational period (dashed and solid lines respectively) densities are plotted for each zone. Lines connect zones in the same depth grouping: inshore, middle, and inner and outer offshore zones. Stars indicate zones with significantly different preoperational and operational densities (Mann-Whitney U test α = .05). ND = no data, TR = trace, Z = zero.
a) Total zooplankton, b) copepod nauplii, c) cyclopoid copepods C1-C5,

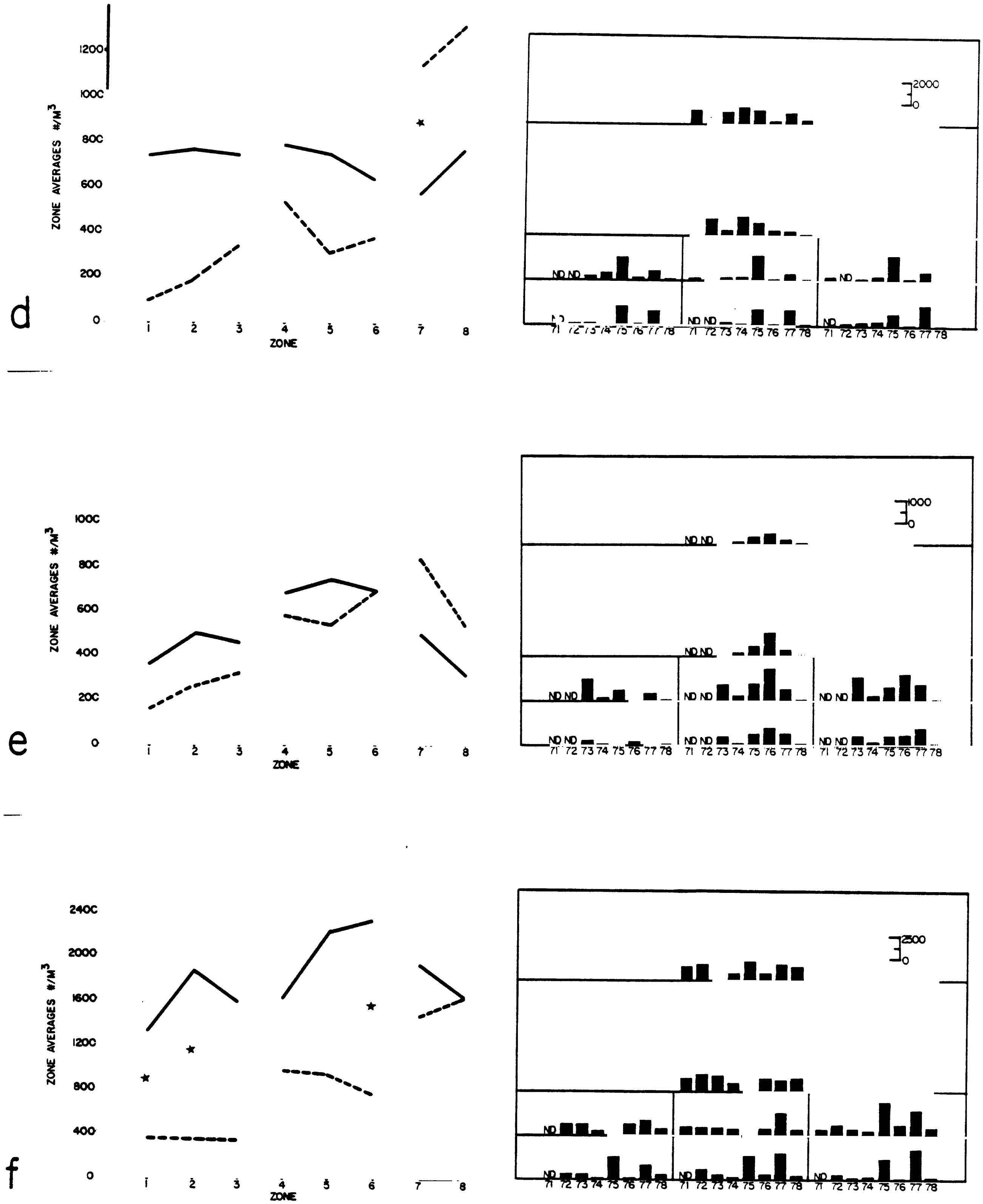

FIG. 39. Continued. d) <u>Cyclops</u> spp. C6, e) <u>Diaptomus</u> spp. C1-C5, f) Diaptomus spp. C6,

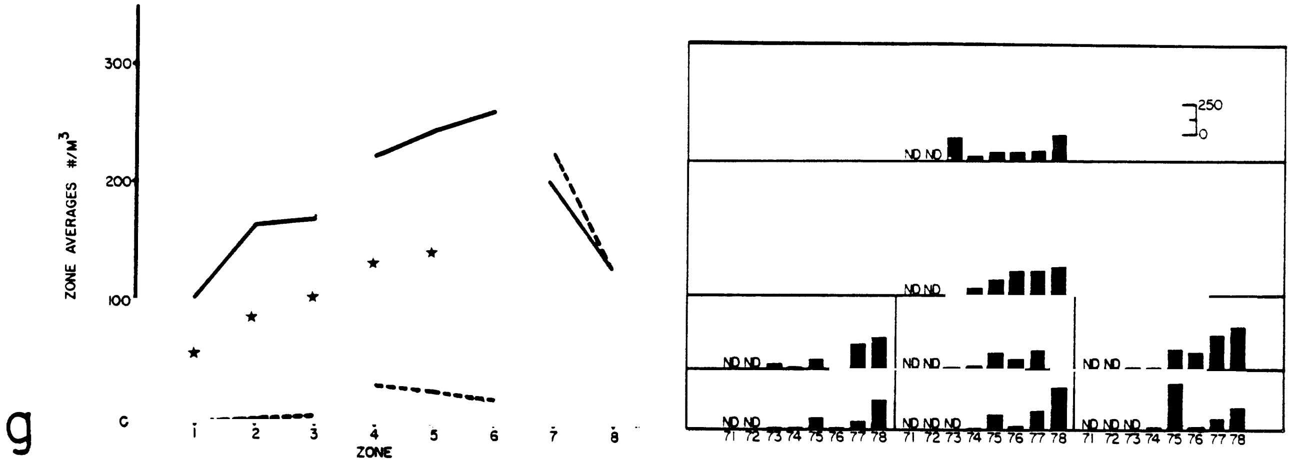

FIG. 39. Concluded. g) Limnocalanus macrurus C1–C6.

Table 7. Results of the Mann-Whitney U tests comparing April preoperational and operational densities of nine zooplankton taxa in each of eight zones. The preoperational period is 1971-74 or a subset ending in 1974, and the operational period is 1975-78.

Taxon	Zone								Period
Order and Suborder Level	1	2	3	4	5	6	7	8	
Copepod nauplii	*	*	*	*	*	*	*	NS	72-78
Cyclopoids (C1-C6)	NS	NS	NS	NS	NS	NS	*	*	71-78
Calanoids (C1-C6)	*	*	*	NS	*	*	NS	NS	71-78
<u>Genus, species, or developmental stage</u>									
Cyclopoids (C1-C5)	NS	*	NS	NS	NS	*	*	NS	73-78
<u>Cyclops</u> spp. C6	NS	NS	NS	NS	NS	NS	*	NS	73-78
<u>Diaptomus</u> spp. (C1-C5)	NS	NS	NS	NS	NS	NS	NS	NS	73-78
<u>Diaptomus</u> spp. C6	*	*	NS	NS	NS	*	NS	NS	73-78
<u>Limnocalanus macrurus</u> (C1-C6)	*	*	*	*	*	*	NS	NS	73-78
Total zooplankton	*	*	*	NS	*	*	NS	NS	72-78

*significant difference, $\alpha = 0.05$
NS not significant

significantly lower operational densities in the plume inshore (a factor of less than 1), the northern middle, and the inner offshore zones (a factor of about 2).

The mean concentrations of adult <u>Diaptomus</u> spp. were up to six times higher for the operational period for all zones, but differences were statistically significant for only the southern inshore, plume inshore, and the northern middle zones (Fig. 39). <u>Diaptomus</u> spp. adults were particularly abundant in 1975 and 1977. While the mean concentration of immature <u>Diaptomus</u> spp. copepodites (Fig. 39) was higher during the operational period for the six inshore and middle depth zones (a factor of about 2), these differences were not statistically significant. <u>Limnocalanus macrurus</u> copepodites were particularly

abundant in 1978 (Fig. 39). The operational mean densities of L. macrurus were significantly higher, by factors of 8 to 35, in the six inshore and middle zones.

Statistical Comparisons of July Preoperational and Operational Abundances

The preoperational and operational abundances of 13 zooplankton taxa were compared for each of the eight zones of the survey grid. All taxa except copepod nauplii and Eurytemora affinis copepodites exhibited statistically significant ($p < 0.05$) differences in densities between time periods for at least some of the zones (Table 8). Significant differences were detected in each of the eight zones. Total zooplankton had lower mean densities during the operational period (a factor of less than 2) in all zones except the southern inshore zone, but these differences were significant in only the plume middle zone and the outer offshore zone.

Cladocera showed statistically significant lower abundances during the preoperational period in the plume inshore and the outer offshore zone. The numerically dominant cladoceran Bosmina longirostris was the major contributor to the observed decline of cladoceran numbers in the outer offshore zone. B. longirostris had significantly lower abundances (by a factor of about 4) during the operational period in only the outer offshore zone. Daphnia spp. was the second most important cladoceran taxa in July. The mean operational densities of Daphnia spp. were from 2 to 4 times higher in all zones than the preoperational densities (Fig. 40) but were significantly different in only the southern and plume inshore zones, the southern middle zone, and the outer offshore zone. High densities of Daphnia spp. in 1976 and 1977 produced these trends.

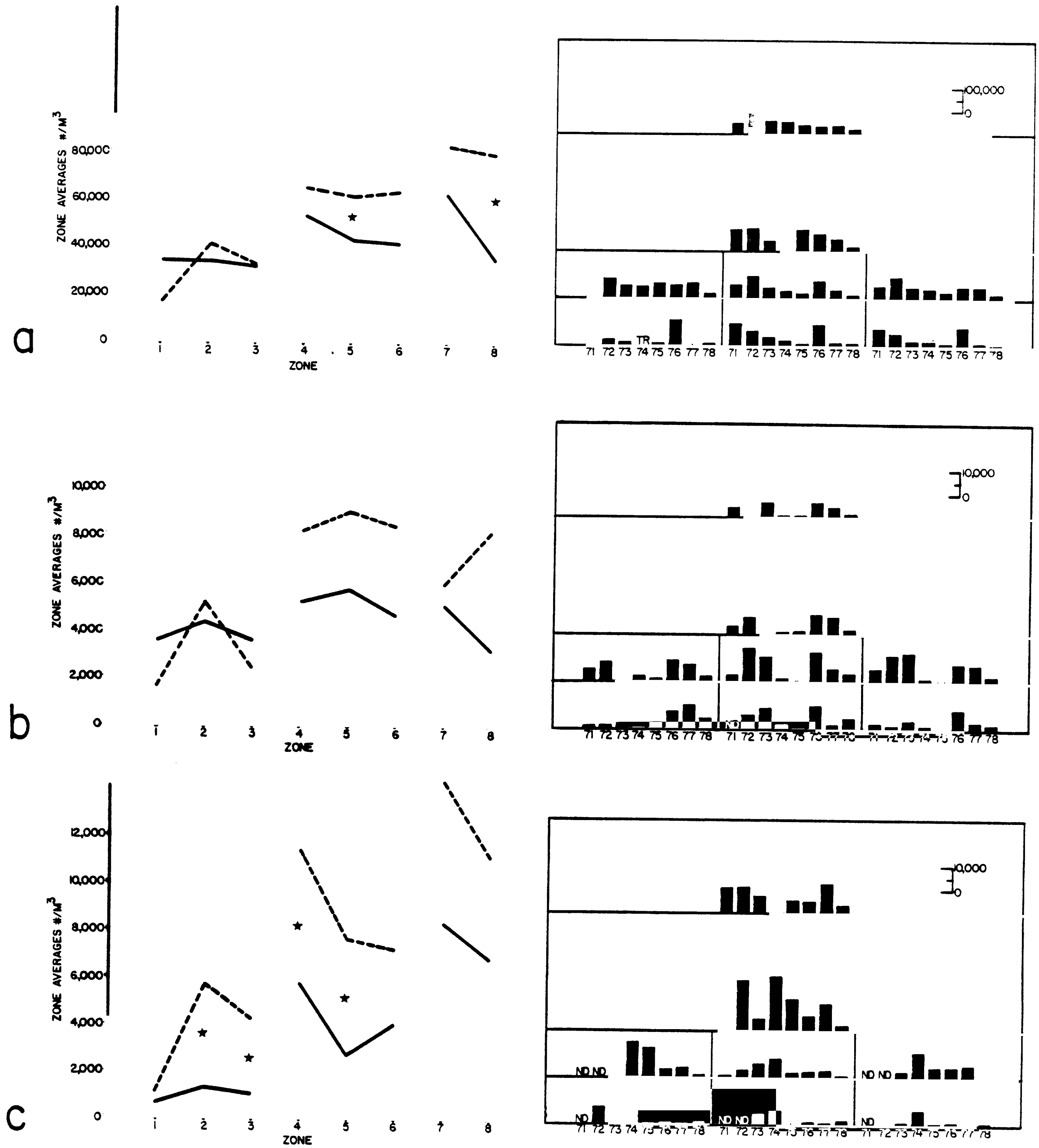

FIG. 40. The mean densities of zooplankton taxa in July of each year, 1971-1978, are given in the histograms. The mean preoperational and operational period (dashed and solid lines respectively) densities are plotted for each zone. Lines connect zones in the same depth grouping: inshore, middle, and inner and outer offshore zones. Stars indicate zones with significantly different preoperational and operational densities (Mann-Whitney U test α = .05). ND = no data, TR = trace, Z = zero.
a) Total zooplankton, b) copepod nauplii, c) cyclopoid copepods C1-C5,

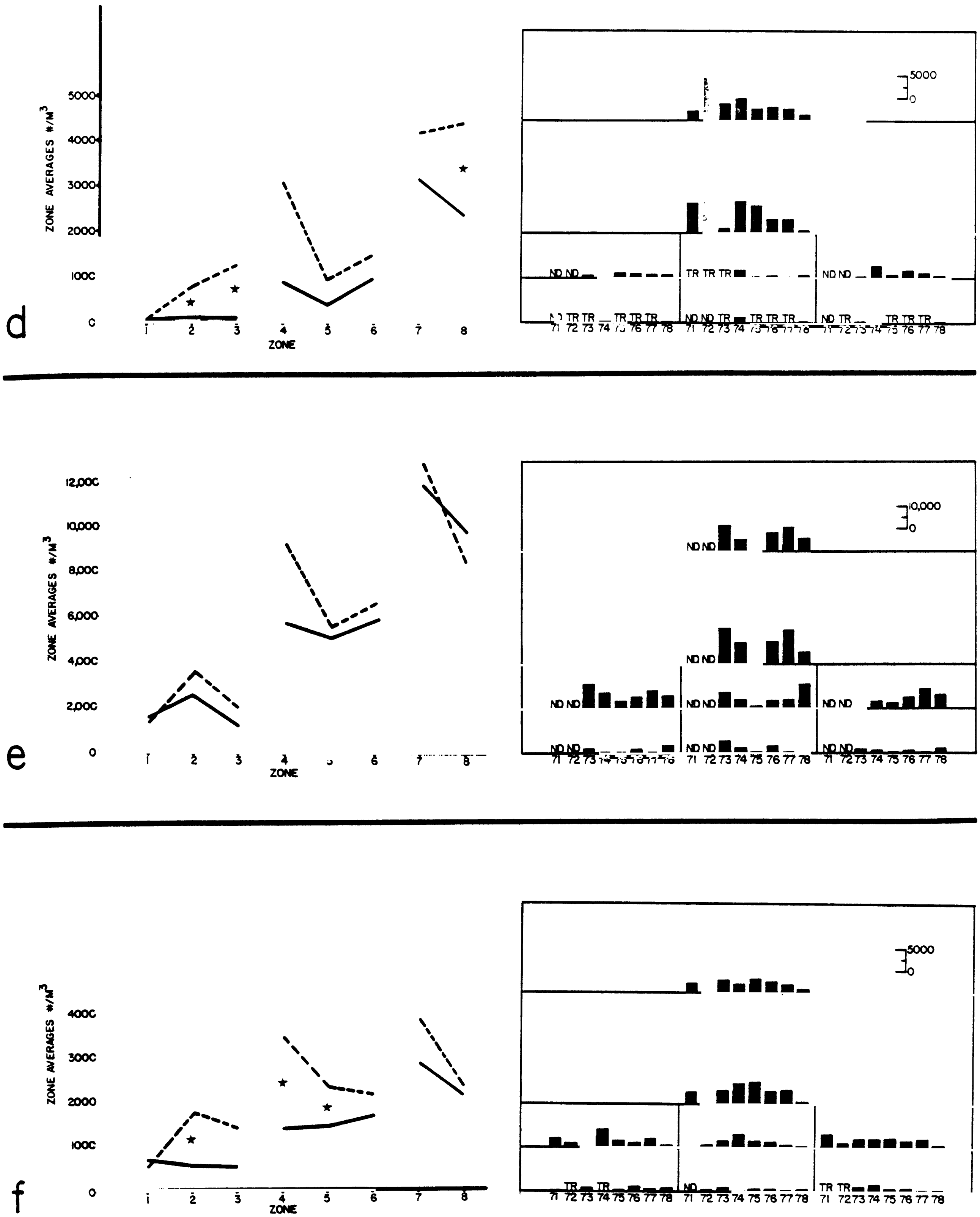

FIG. 40. Continued. d) <u>Cyclops</u> spp. C6, e) <u>Diaptomus</u> spp. C1-C5, f) <u>Diaptomus</u> spp. C6,

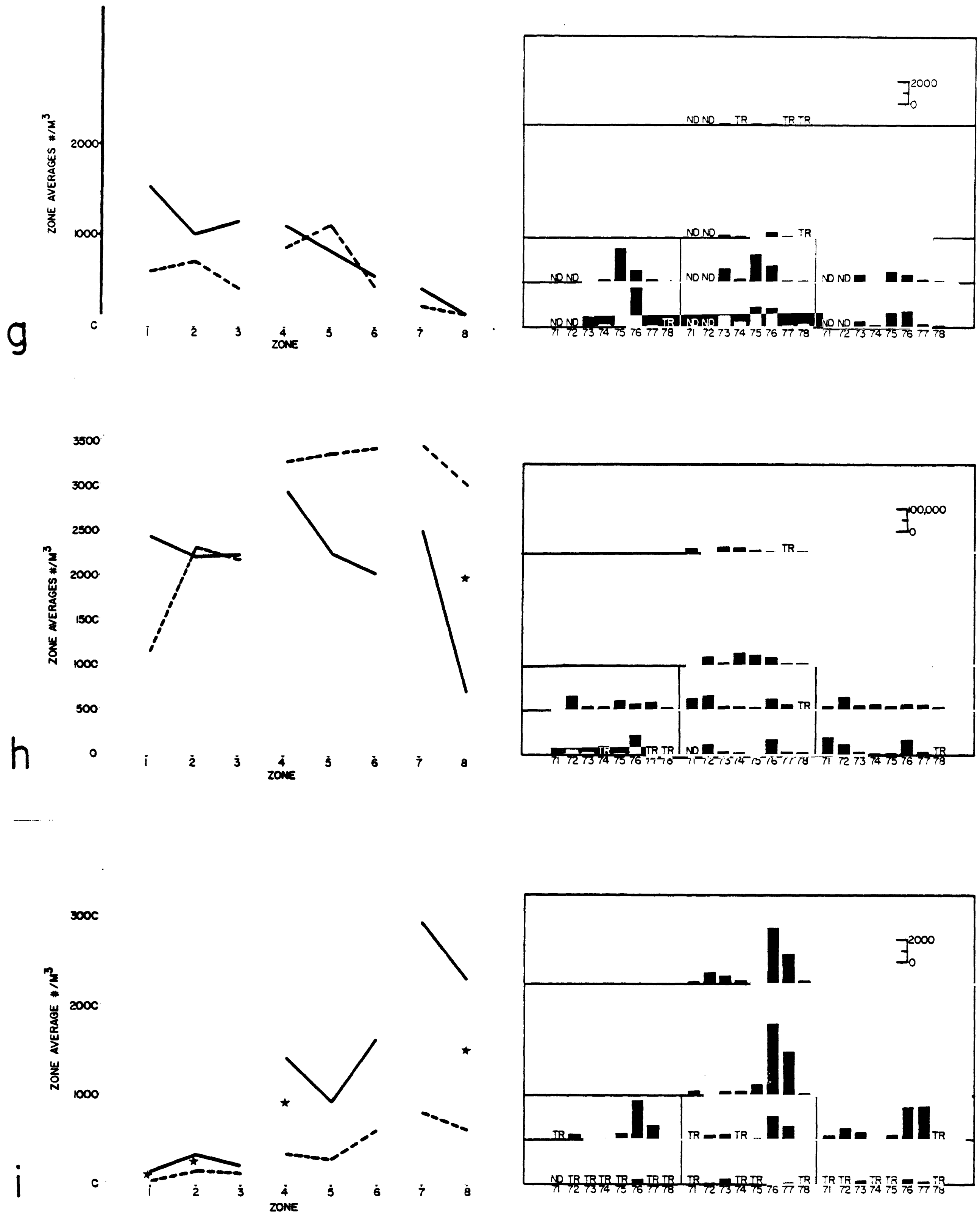

FIG. 40. Continued. g) Eurytemora affinis C1-C6,
h) Bosmina longirostris, i) Daphnia spp.,

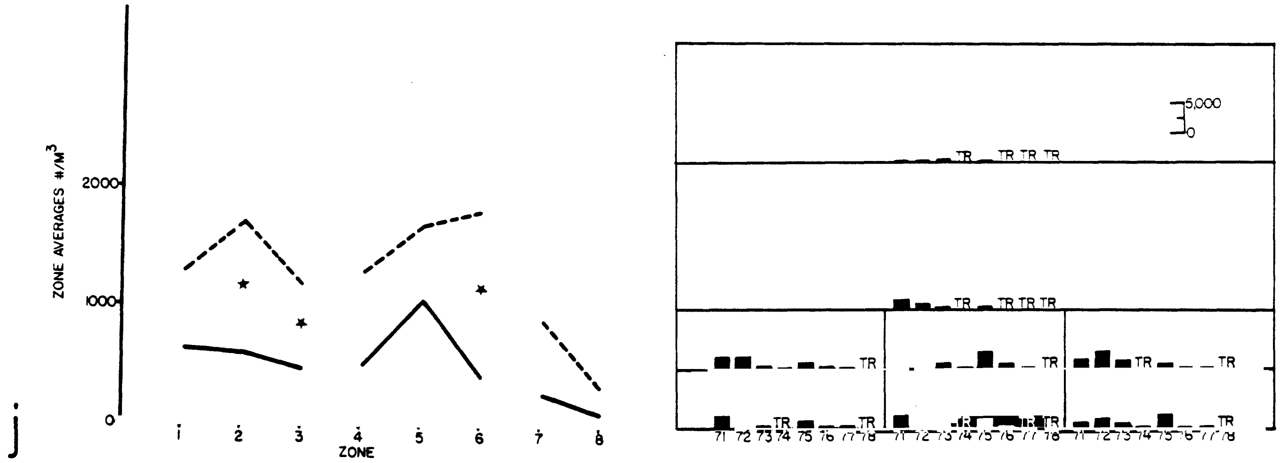

FIG. 40. Concluded. j) Asplanchna spp.

Table 8. Results of the Mann-Whitney U tests comparing July preoperational and operational densities of thirteen zooplankton taxa in each of eight zones. The preoperational period is 1971-74 or a subset ending in 1974, and the operational period is 1975-78.

Taxon	Zone								Period
Order and Suborder Level	1	2	3	4	5	6	7	8	
Cladocerans	NS	*	NS	NS	NS	NS	NS	*	71-78
Copepod nauplii	NS	NS	NS	NS	NS	NS	NS	NS	72-78
Cyclopoids (C1-C6)	NS	*	*	NS	*	NS	*	*	71-78
Calanoids (C1-C6)	*	NS	NS	NS	NS	NS	NS	NS	71-78
Genus, species, or developmental stage									
Bosmina longirostris	NS	NS	NS	NS	NS	NS	NS	*	72-78
Daphnia spp.	*	*	NS	*	NS	NS	NS	*	71-78
Cyclopoids (C1-C5)	NS	*	*	*	*	NS	NS	NS	73-78
Cyclops spp. C6	NS	*	*	NS	NS	NS	NS	*	73-78
Diaptomus spp. (C1-C5)	NS	*	NS	NS	NS	NS	NS	NS	73-78
Diaptomus spp. C6	NS	*	NS	*	*	NS	NS	NS	73-78
Eurytemora affinis (C1-C6)	NS	NS	NS	NS	NS	NS	NS	NS	73-78
Asplanchna spp.	NS	*	*	NS	NS	*	NS	NS	71-78
Total zooplankton	NS	NS	NS	NS	*	NS	NS	*	72-78

*significant difference, $\alpha = 0.05$
NS not significant

Cyclopoid copepodites had lower mean concentrations in all zones during the operational period, with statistically significant differences in all but the southern inshore and middle zones and the northern middle zone. Immature copepodites were the most common form in July. Both immature and adult copepodites had lower mean abundances, by factors up to 13, during the operational period in all zones (Fig. 40). Adult *Cyclops* spp. was particularly abundant in 1972 and 1974.

Calanoid copepodites occurred in significantly different concentrations (Table 8) only in the southern inshore zone where they increased in abundance

during the operational years. The numerically dominant taxon was *Diaptomus* spp. immature copepodites (Fig. 40). These immatures had significantly different densities in only the inshore plume zone where they had lower operational abundances (by a factor of less than 1). Adult *Diaptomus* spp. (Fig. 40) had lower operational mean densities in all zones except the southern inshore zone, with statistically significant differences (by a factor of 1 to 2) in the plume zones and the southern middle zone. While *Eurytemora affinis* (Fig. 40) mean abundances were higher during the operational period than the preoperational period, these differences were not statistically significant.

Asplanchna spp. was less abundant during the operational period by factors of 2 to 4 in all zones (Fig. 40j). These differences were significant in the northern inshore, the northern middle, and the plume inshore zones.

Statistical Comparisons of October Preoperational and Operational Abundances

The preoperational and operational abundances of twelve zooplankton taxa were examined for each of the eight zones of the survey grid. All taxa occurred in statistically significant ($p<0.05$) different concentrations between the preoperational and operational periods in at least one zone (Table 9). Total zooplankton mean densities were higher during the operational period (by a factor of less than 1) in all zones except the outer offshore zone (Fig. 41), although differences were statistically significant in only the southern middle, the northern middle, and the inner offshore zones.

Cladocerans were more abundant during the operational period in all zones except the offshore zone, where a lower operational mean density was statistically significant. *Bosmina longirostris* and *Eubosmina coregoni* were the numerically dominant cladocerans in October. Both species exhibited significant

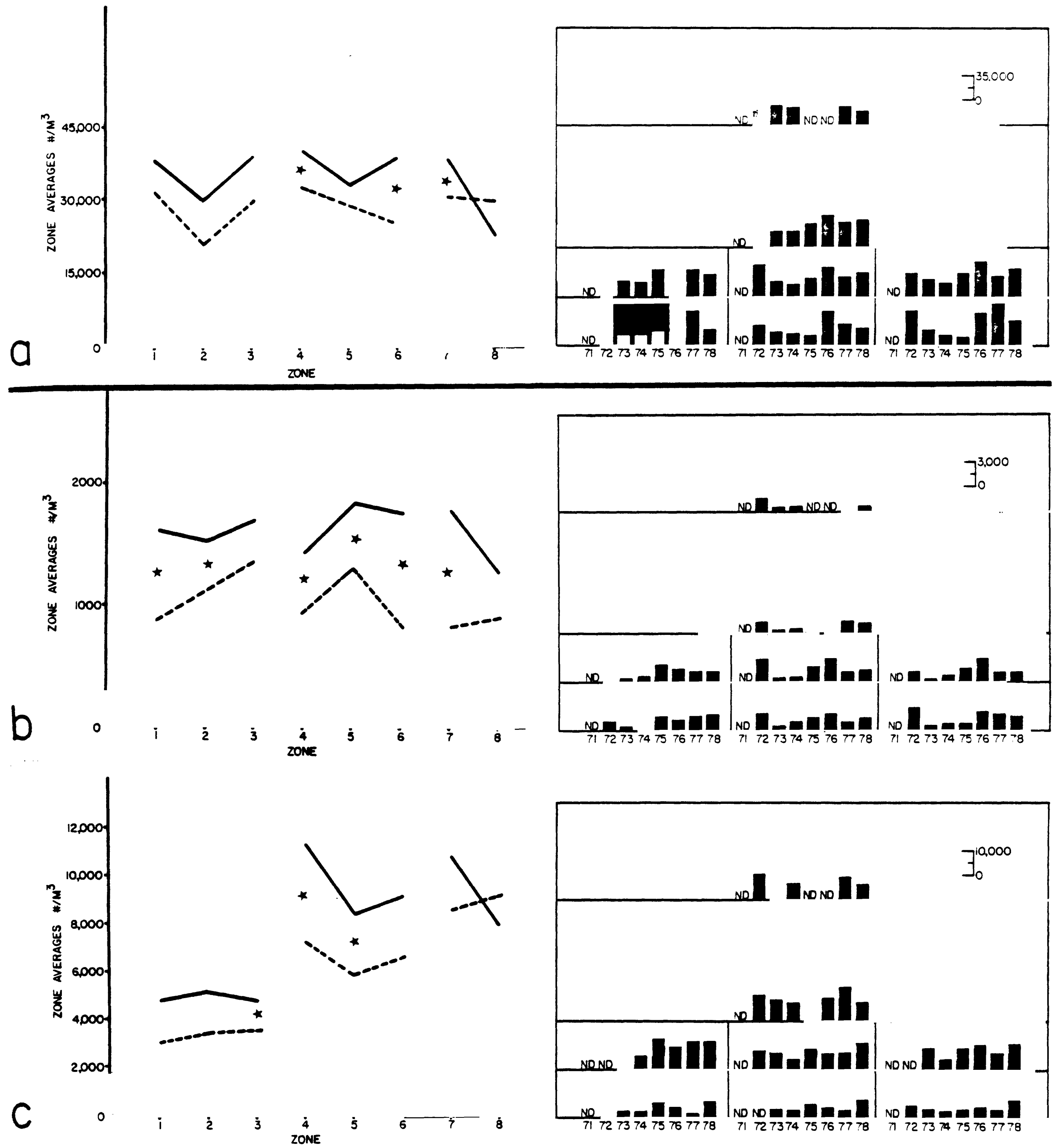

FIG. 41. The mean densities of zooplankton taxa in October of each year, 1971-1978, are given in the histograms. The mean preoperational and operational period (dashed and solid lines respectively) densities are plotted for each zone. Lines connect zones in the same depth grouping: inshore, middle, and inner and outer offshore zones. Stars indicate zones with significantly different preoperational and operational densities (Mann-Whitney U test α = .05). ND = no data, TR = trace, Z = zero.
a) Total zooplankton, b) copepod nauplii, c) cyclopoid copepods C1-C5,

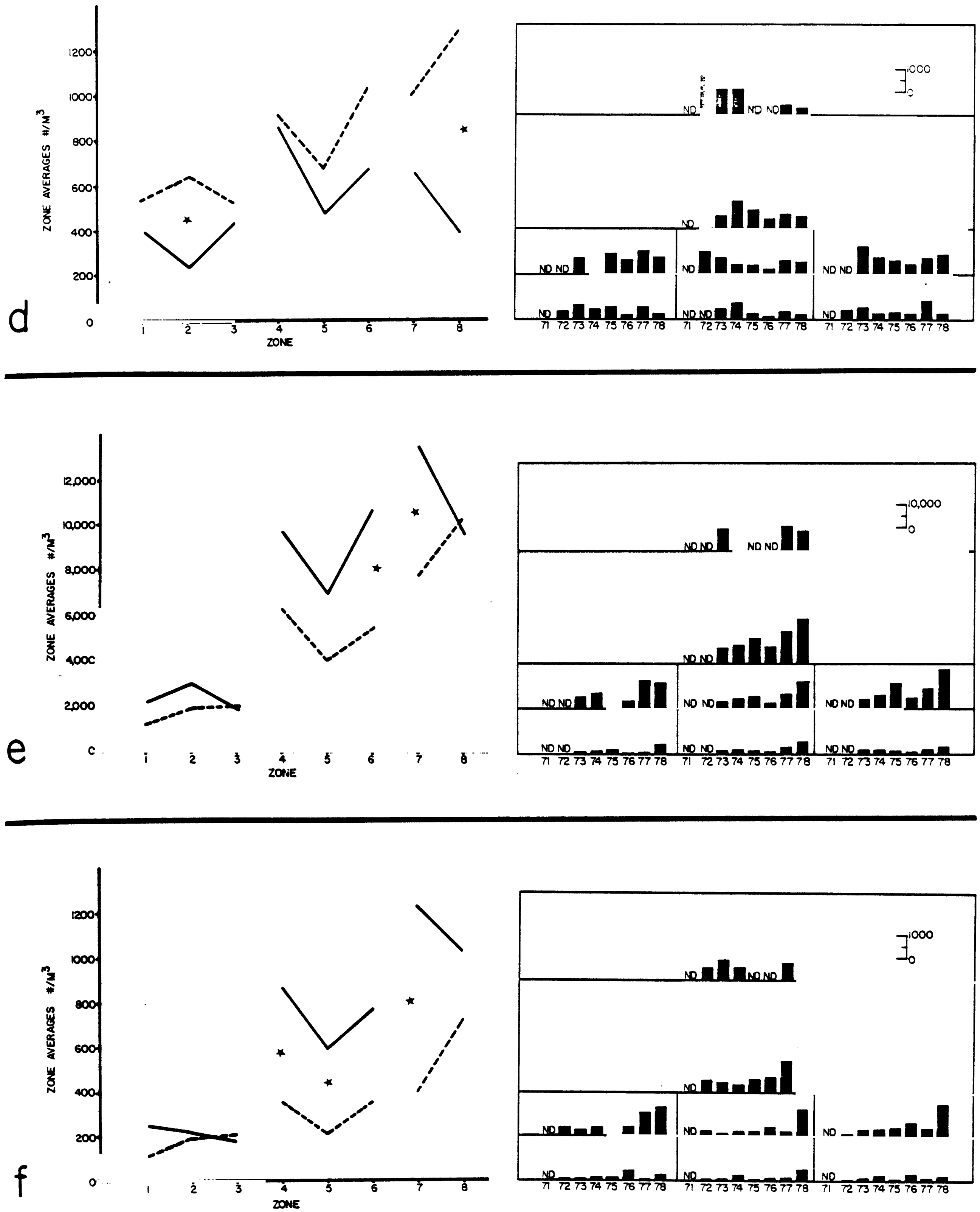

FIG. 41. Continued. d) Cyclops spp. C6, e) Diaptomus spp. C1-C5, f) Diaptomus spp. C6,

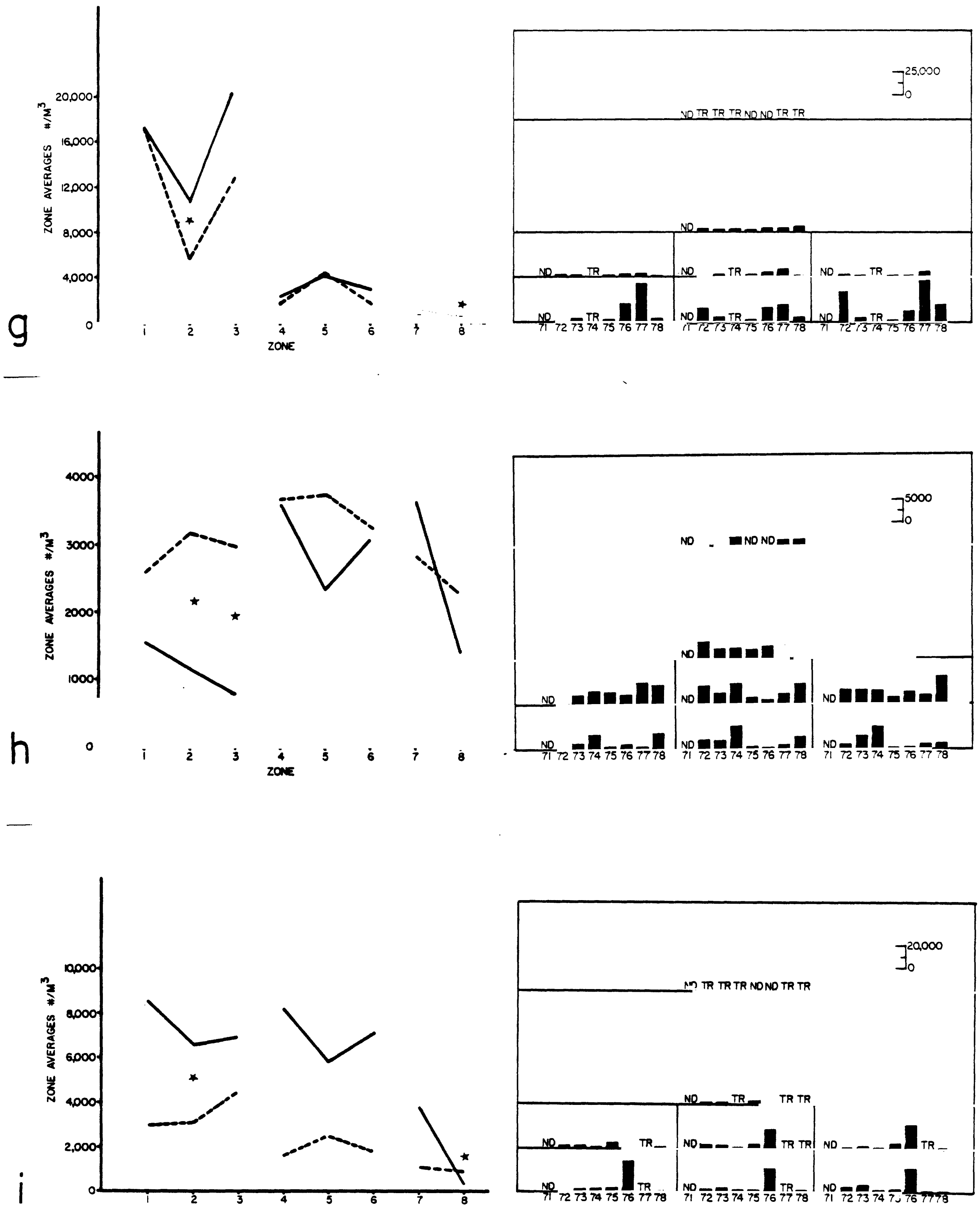

FIG. 41. Continued. g) Bosmina longirostris, h) Daphnia spp., i) Eubosmina coregoni,

j

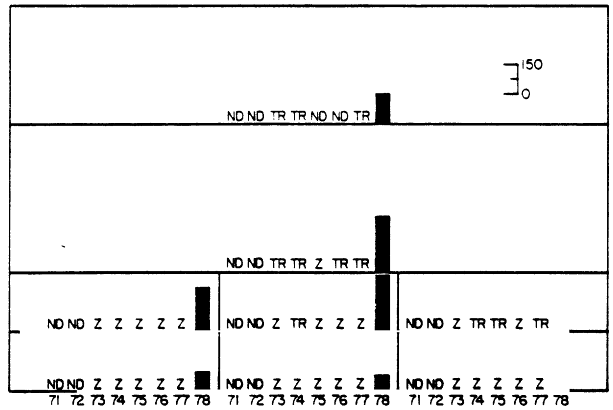

FIG. 41. Concluded. j) Mesocyclops edax C1-C6.

Table 9. Results of the Mann-Whitney U tests comparing October preoperational and operational densities of twelve zooplankton taxa in each of eight zones. The preoperational period is 1972-74 or a subset ending in 1974, and the operational period is 1975-78. Stations in zone 8 were not sampled in 1975 or 1976 (see text).

Taxon	Zone								Period
Order and Suborder Level	1	2	3	4	5	6	7	8	
Cladocerans	NS	NS	NS	NS	NS	NS	NS	*	72-78
Copepod nauplii	*	*	NS	*	*	*	*	NS	72-78
Cyclopoids (C1-C6)	NS	NS	NS	*	*	*	NS	NS	72-78
Calanoids (C1-C6)	*	NS	NS	NS	NS	NS	NS	NS	72-78
Genus, species, or developmental stage									
Bosmina longirostris	NS	*	NS	NS	NS	NS	NS	*	72-78
Eubosmina coregoni	NS	*	NS	NS	NS	NS	NS	*	72-78
Daphnia spp.	NS	*	*	NS	NS	NS	NS	NS	72-78
Cyclopoids (C1-C5)	NS	NS	*	*	*	NS	NS	NS	73-78
Cyclops spp. C6	NS	*	NS	NS	NS	NS	NS	*	73-78
Diaptomus spp. (C1-C5)	NS	NS	NS	NS	NS	*	*	NS	73-78
Diaptomus spp. C6	NS	NS	NS	*	*	NS	*	NS	73-78
Total zooplankton	NS	NS	NS	*	NS	*	*	NS	72-78

*significant difference, $\alpha = 0.05$
NS not significant

differences in concentration between preoperational and operational periods in only the plume inshore zone, where both species had higher operational densities, and in the outer offshore zone, where operational densities were lower. Except for the outer offshore zone, the mean operational concentrations of *E. coregoni* were 2 to 5 times higher than the preoperational densities (Fig. 41). The major factor producing this trend was an unusually high abundance of *E. coregoni* in October 1976. Although *Daphnia* spp. occurred in lower densities in the operational period in all zones except the inner offshore zone, these differences were statistically significant (by a factor of 2 to 3)

in only the plume and northern inshore zones (Fig. 41h).

Cyclopoid copepodites (Figs. 41c, d) had a statistically significant higher mean concentration during the operational period in all three middle depth zones. Immature copepodites were the numerically dominant form. Immature cyclopoid copepodites were more abundant in the operational period in all zones except the outer offshore zone, although differences (by factors of less than 2) were significant only in the northern inshore zone, the southern middle, and plume middle zones. In contrast, adult Cyclops spp. were less abundant (by about half) during the operational period in all zones, with significant differences only in the plume inshore and outer offshore zones.

As discussed in Section 1, Mesocyclops edax copepodites were observed in the October 1978 survey in unusually high concentrations (up to $481/m^3$) compared to densities observed in previous years and in other months. The rarity of this species makes it inappropriate statistically to compare preoperational and operational zone concentrations. However, mean yearly zone densities are presented in Fig. 41j for visual inspection. M. edax copepodites occurred in highest densities in the 10- to 40-m depth zones in October 1978 and occurred in comparable concentrations in survey zones of similar depth. The absence of this copepod within the shallowest depth zones in previous October surveys and its relatively high concentrations over the whole survey area in 1978 are striking trends that appear completely unrelated to plant operation.

Calanoid copepodites (Figs. 41e, f) had statistically similar densities in the preoperational and operational years in all zones except the southern inshore zone. Diaptomus spp. immature copepodites were the numerically dominant form. Diaptomus spp. immatures had statistically significant higher abundances (by a factor of less than 2) in the operational period in the northern middle

zone and the inner offshore zone. Adult Diaptomus spp. had significantly higher abundances (by a factor of 2 to 3) during the operational years in the southern middle, the plume middle, and the inner offshore zones. Adults were particularly abundant in 1978. Nauplii had higher mean densities during the operational period in all zones, with differences statistically significant in all but zones 3 and 8 (Fig. 41b).

DISCUSSION

Comparison of the four years (1971-1974) of preoperational data with the four years (1975-1978) of operational data indicates that there were statistically significant differences in zooplankton abundances between the two time periods. During April cruises, zooplankton tended to be more abundant in the operational period with the greatest increase in numbers associated with adult Diaptomus spp., nauplii, immature Cyclops and Diaptomus spp. copepodites, and Limnocalanus macrurus. For July cruises, zooplankton tended to be less abundant in the operational period with the exception of Daphnia spp., which were more abundant. In October, zooplankton tended to be more abundant in the operational period with the exception of Daphnia and adult Cyclops species, which were less abundant. The greatest operational increases observed during October cruises were in numbers of nauplii, immature Cyclops spp. and Diaptomus spp. copepodites, and Eubosmina coregoni. Furthermore, Mesocyclops edax occurred in greater numbers in October and November 1978 than previously observed in the survey area. Daphnia pulex was observed for the first time in October and November 1978 and, while not abundant, was widespread.

Our studies indicate that there were both quantitative and qualitative differences in zooplankton abundances between the preoperational (1971-1974) and

operational (1975-1978) periods. Such differences could be related to a variety of factors including power plant operation. At this time, it is useful to consider other studies which have reported changes in Great Lakes zooplankton. Such studies are of interest in identifying both the specific changes in zooplankton populations and the factors influencing such changes.

Changes in zooplankton populations have been reported for Lakes Ontario, Erie, and Michigan. For the most part, these studies are based on comparing zooplankton collections made by different researchers over various time periods. Often, these researchers employed different collection techniques and sampled different areas of the lake. This poses some difficulty in interpreting the significance of differences between studies. Comparisons of single collections made in different years and in different parts of a lake, while often made, provide little evidence per se that differences are due to temporal changes in zooplankton populations.

McNaught and Buzzard (1973), for example, reported that zooplankton populations in Lake Ontario have changed between 1939 and the 1969 to 1972 period. While summer standing stocks of zooplankton were similar in both periods, copepods decreased from about 81.1% of the crustacean zooplankton in 1939 to 16.2% to 52.2% in the 1969 to 1972 period. McNaught later (1975) related these changes to eutrophication. However, the 1939 data were based on a study conducted by Tressler and Austin (1940) in which a single station in Lake Ontario was examined on a single date. Given the inherent spatial and temporal variability in zooplankton populations, interpretations of differences between years should be viewed with caution.

Stronger evidence for changes in zooplankton populations is found in Bradshaw's (1964) study of Lake Erie. Bradshaw compared the 49 collections made

between September 2, 1938 and September 25, 1929 by Chandler (1940) with 30 collections he and Verduin made between October 26, 1948 and October 3, 1949 (Bradshaw 1964), and the daily collections made by Hubschman (1960) between June 30 and August 21, 1959. Both quantitative and qualitative changes were noted in zooplankton populations. The maximum number of zooplankton observed in an annual collection period increased from $17,000/m^3$ in 1938-1939 to $48,150/m^3$ in 1948-1949, and to $202,000/m^3$ in 1959. Furthermore, the average number of cladocerans for the July to August period increased from $4,244/m^3$ in 1938-1939 to $19,229/m^3$ in 1948-1949, and to $39,161/m^3$ in 1959. Daphnia galeata mendotae was the dominant form in 1938-1939 period while Daphnia retrocurva dominated at later dates. In addition, Diaphanosoma leuchtenbergianum (=D. birgei) and Chydorus sphaericus increased in abundance in 1959. Daphnia pulex, which occurred in 1939 spring-summer concentrations of less than $3,000/m^3$, was not observed after 1939. Copepod data were less complete but these zooplankters appeared to have undergone less change: winter and spring populations were similar in 1939 and 1949. Eurytemora affinis, a brackish-water copepod, appeared in Lake Erie by 1961 (Engel 1962) and subsequently has been observed in other Great Lakes. Bradshaw related some of the differences in zooplankton populations in 1939 and 1949 to increased phytoplankton standing stocks. Davis (1964) documented the large increase in phytoplankton in Lake Erie over the past few decades.

Changes in zooplankton populations also have been reported for Lake Michigan. Brooks (1969) reported an increase in the dominance of Daphnia galeata mendotae and D. retrocurva and a decrease in the dominance of Eubosmina coregoni between 1927 and 1954 and related these changes to eutrophication. However, Brooks drew his conclusions by comparing Eddy's (1927) data, collected

from the Chicago breakwater and from Indiana State Dunes Park, with Wells' (1960) data collected from a station 12.8 km offshore of Grand Haven. Because zooplankton differ in abundance and composition with distance from shore (Section 1; Evans *et al*. 1980), Brooks' study does not provide strong evidence for population change.

Wells (1970) studied zooplankton populations at the same station 12.8 km offshore of Grand Haven in Lake Michigan during 1954, 1966, and 1968. He observed a decrease in the abundance of large zooplankton (*Leptodora kindtii*, *Daphnia galeata mendotae*, *D. retrocurva*, *Limnocalanus macrurus*, *Epischura lacustris*, *Diaptomus sicilis*, and *Mesocyclops edax*) between 1954 and 1966 that coincided with a burgeoning alewife population. After the massive dieoff of alewife in the spring of 1967, alewife populations remained relatively low. By 1968, there was a strong increase in the abundance of medium-sized zooplankton such as *Daphnia longiremis*, *Holopedium gibberum*, *Polyphemus pediculus*, *Bosmina longirostris*, *Eubosmina coregoni*, *Ceriodaphnia* spp., *Cyclops bicuspidatus thomasi*, *C. vernalis*, and *Diaptomus ashlandi*. Larger zooplankton also increased in numbers with the exception of *Mesocyclops edax* and *Daphnia galeata mendotae*. Incidentally, Wells was the first to observe *Eurytemora affinis* in Lake Michigan in 1966.

Two main factors have been identified in these studies as producing changes in zooplankton community structure: eutrophication and fish predation. A large body of literature exists documenting the relationship between zooplankton standing stocks and the trophic status of a lake, and between zooplankton community structure and planktivorous fish predators. Each factor affects the zooplankton community in different ways as one is related to food availability and the other to mortality. Eutrophication tends to exert its most pronounced

effect on zooplankton abundance while fish predation exerts its strongest effect on zooplankton composition.

Hrbacek (1962) and Brooks and Dodson (1965) were the first to demonstrate that planktivorous fish selectively consume the largest components of the zooplankton, lowering the community size-frequency distribution. Because many of the large zooplankton are predators on smaller zooplankton, an additional effect is achieved. As fish remove invertebrate predators, smaller zooplankton increase in numbers. Introduction of planktivorous fish into a lake can produce a rapid change in zooplankton community structure (Brooks and Dodson 1965). In some instances, zooplankton populations can recover when planktivorous predation is reduced (Wells 1970). There is little evidence, if any, that planktivorous fish affect zooplankton standing stocks. Zooplankton standing stocks in lakes with planktivorous fish are approximately the same as standing stocks in similar lakes in which fish predators are absent (Pope and Carter 1975). However, zooplankton species composition (and probably production) differs between lakes.

Eutrophication is a process by which a body of water becomes progressively richer in nutrients. In lakes, this is evidenced by greater phytoplankton standing stocks. Because zooplankton fecundity is a function of food level, zooplankton abundances are directly related to phytoplankton standing stocks, with more productive waters supporting greater zooplankton standing stocks (Pederson *et al*. 1976). Patalas (1972) showed that there were strong correlations between summer zooplankton standing stocks in Lakes Superior, Erie, and Ontario and chlorophyll concentrations and phosphorous loadings.

The direct effects of power plant operation on zooplankton populations have been investigated in a number of studies spanning a range of conditions. Cory and Nauman (1969) studied epifauna in the Patuxent estuary and observed that

sedimentary organisms were about three times more abundant in the heated discharge than in the intake. These differences were related to natural changes in salinity and turbidity, to thermal additions, and possibly to the destruction of predaceous zooplankton during plant passage. Patalas (1970) observed that a heated lake had a higher biomass of zooplankton than a similar-sized unheated lake: summer epilimnion temperatures were approximately 5-6C° higher in the heated lake and reached 26 to 28.5°C. Also, the heated lake had greater primary productivity than the unheated lake. Markowski (1962) reported faunal changes in the heated waters of Cavendish Dock although he was unable to determine the specific effects of thermal discharge.

Whitehouse (1971) conducted a detailed study of Lake Trawsfyndd, a power station cooling pond. In general, there were no differences in zooplankton population dynamics between the warmest discharge lagoon station and the coolest open-lake control station: these stations spanned a thermal gradient of approximately 5C°. However, Diaphanosoma brachyurum and Ceriodaphnia quadrangula populations were markedly smaller in the heated lagoon. The author concluded that it was difficult to relate these differences to thermal discharge without more experimental data on the thermal tolerances of the two cladoceran species.

Zhitenjowa and Nikanorow (1972) studied a reservoir in the upper Volga. The plume from the power plant was thermally detectable for 3 to 14 km downriver of the plant site. Zooplankton mortality as a result of plant passage was high. Furthermore, when epilimnion temperatures reached 25°C, zooplankton migrated into deeper regions of the water column. Zooplankton biomass was reduced as temperatures exceeded 28-30°C. The authors concluded that power plant operation had adversely affected the river community through thermal effects.

Lanner and Pejler (1973) investigated zooplankton populations in an open-ice area created by the outfall of a power plant. Polyarthra remata, a warmwater stenotherm, was observed at the outfall (9°C) but previously had not been collected in the area. In addition, the rotifers Synchaeta spp., Asplanchna spp., Polyarthra spp., and Notholca squamula, the cladoceran Bosmina longirostris, and copepod nauplii occurred in maximum abundance at the outfall. Factors influencing these changes were not identified but were related to temperature.

McMahon and Docherty (1975) studied the effects of heat enrichment on species succession in enclosures set in a northern temperate lake. Three rotifers, Asplanchna spp., Keratella cochlearis, and Polyarthra major, increased significantly in numbers in the heated enclosures (Δ-T 6C°) in late spring and in mid-summer. In summer, thermal addition apparently advanced seasonality in one set of enclosures. In one enclosure, where temperatures approached 28.5°C to 35°C, Asplanchna spp. was less abundant than in the control enclosures or in the lake. Polyarthra major became abundant in this experimental enclosure only after temperatures decreased by 6 to 7C°.

Mathur et al. (1980) investigated the effects of thermal discharge on zooplankton in Conowingo Pond where the Δ-T approached 10.0C° in winter and 8.0C° in summer. Ambient-water temperatures did not exceed 25°C. The authors utilized analysis of covariance to investigate changes at the experimental stations. Adjustments were made for ambient-water temperature and zooplankton abundances at the upriver control site. The authors concluded that the power plant had not produced any significant change in zooplankton populations during most collection periods. There were only a few points where zooplankton abundances at the experimental stations were outside the 90% confidence interval

for abundance estimates predicted by the regression model. Unlike other researchers, the authors did not analyze their data at the species level.

Power plant operation, therefore, can affect zooplankton communities in several ways. First, depending on plant design, a significant fraction of zooplankton passing through the plant may be killed as a result of thermal and mechanical stresses. If these zooplankton are discharged into a relatively small volume of water, these losses may be detected in the aquatic community (Zhitenjowa and Nikanorow 1972). Secondly, the heated discharge may raise ambient water temperatures for sufficient time periods to affect the zooplankton community. Moderate thermal additions result in an increase of zooplankton standing stock (McMahon and Docherty 1975, Lanner and Pejler 1973, Patalas 1970), possibly as a direct result of increased primary productivity. Conversely, high thermal elevations where temperatures approach or exceed 28°C may cause increased mortality and result in large decreases in zooplankton abundance (Zhitenjowa and Nikanorow 1972). Intermediate thermal elevations may exert sublethal stresses on the community (Whitehouse 1971, McMahon and Docherty 1975) with moderate reductions in the abundance of certain species.

The Donald C. Cook Plant does not immediately kill a large percentage of the zooplankton which pass through its condensers. The estimated mean mortality ranges from 2 to 12% (Section 3). As discussed in Section 1, these losses cannot be detected in the vicinity of the discharge jets. The plume, itself, is only slightly warmer (2 to 3C°) than ambient water and quickly mixes into the lake. Zooplankton are exposed to moderate thermal elevations for too short a period of time (hours) to exhibit any measurably enhanced growth as reported in the McMahon and Docherty (1975) study. Rotifers, which do have relatively short generation times and have been shown in other studies to respond to thermal

stimulation, are not investigated as part of the required Technical Specifications. Rotifer studies were initiated at a subset of stations in 1979 and these data will be discussed in a subsequent report.

Although the Cook Plant does not have a measurable effect on zooplankton community structure in the vicinity of the discharge jets, as determined by the survey program, it is clear that zooplankton populations in the nearshore region are different in the operational period when compared to preoperational populations. The question then becomes: has the Cook plant had an indirect effect on zooplankton populations in the nearshore region? For example, have planktivorous fish become less abundant since these plants went into operation, thus lowering the predation pressure on the zooplankton community? Such a question cannot be directly answered with the data base that is available for analysis.

It is clear that Lake Michigan is undergoing change due to a variety of factors. The basin has experienced nutrient loading (Chapra and Robertson 1977) and phytoplankton populations have increased (Damann 1960). Although phosphorus reduction programs appear to have been effective in reducing phytoplankton standing stocks near the Chicago Intake (Danforth and Ginsberg 1980), phytoplankton standing stocks continue to increase in the Cook survey area (Ayers and Wiley 1979). Diatoms and flagellates have become more abundant in spring and fall. This in turn may have been a factor contributing to greater zooplankton standing stocks in these two seasons. Bluegreen algae have become more abundant in the summer. As bluegreens are not a good food source, part of the operational reduction in summer zooplankton standing stocks may be related to food quality. Alewife populations have fluctuated in Lake Michigan (Hatch et al. 1981) and recently bloaters have increased in abundance (D. J. Jude, The

University of Michigan, personal communication). These changes in planktivorous fish populations may have had an effect on the zooplankton community, but this also requires further investigation. Thus, although the zooplankton study indicates that zooplankton populations are different between the preoperational and operational periods, it has not determined why these differences have occurred. They clearly are not related to a direct effect of plant operation on the zooplankton community but there is some possibility that plants have indirectly affected the fish population, which in turn has affected the zooplankton community.

SECTION 3

THE EFFECTS OF PLANT PASSAGE

INTRODUCTION

Zooplankton experience various stresses during plant passage including thermal shock, mechanical abrasion, and toxic effects due to chlorination. As a result of these stresses, zooplankton may be temporarily immobilized (a form of shock), physiologically impaired, physically damaged, or killed. The actual degree of damage depends on the sensitivity of the organism, ambient conditions, and plant design and operating characteristics.

While there are various ways of assessing stresses inflicted on the zooplankton community by plant passage, the most common involve determinations of mortality (death) or motility (movement). Measurements of physical damage, *per se*, without considerations of mortality (Standke and Monroe 1981) provide less precise measures of the possible ecological effects of plant passage. Physiological studies investigating the effects of plant passage on growth, longevity, and reproduction have seldom been undertaken (Evans et al. 1978). These studies require long periods of time and are somewhat difficult to interpret ecologically. Numerous laboratory studies investigating thermal effects on organism physiology (Naylor 1965, Heinle 1969) provide some indication of stresses experienced by zooplankton exposed to lengthy thermal elevations such as in cooling ponds or discharge canals.

Zooplankton mortality studies are conducted as part of the monitoring studies at the Donald C. Cook Plant. Mortality is investigated immediately after plant passage (0 hours), 6 hours after plant passage, and 24 hours after plant passage. These studies provide direct information on the effects of plant

design and operating characteristics on zooplankton subjected to plant passage. Furthermore, these determinations allow evaluations of the probable loss to the nearshore zooplankton community as a direct result of mortality due to plant passage. Thus mortality studies complement the field program. Mortalities at 0 hours are of the most interest as these dead zooplankton are localized in the immediate discharge area. Zooplankton dying 6 hours and 24 hours after plant passage probably are transported kilometers away from the plant site. Dilution minimizes the immediate detectable effects of plant passage in these areas of the lake.

MATERIALS AND METHODS

Mortality studies were conducted once a month, 12 months a year. The one exception was the January to February 1977 period when Unit 1 was down and Unit 2 was not operational. Unit 1 discharge was sampled from March 1977 to March 1978, and from August 1978 to December 1978, for a total of 18 occasions. Unit 2 went on line in April 1978 and remained on line until October 1978. This unit was sampled on seven occasions.

Samples were collected from the intake and discharge forebays (Fig. 42) with the Zaggot Trap sampler (Yocum *et al*. 1978). The sampler first was primed with water drawn by a Hale diaphragm pump. A carrier fitted with a 158 μm aperture net was lowered into the chamber to filter the water. The lid was clamped down and hose connections were arranged so that water was drawn from the intake or discharge forebay through a fixed pipe to the sampler, and then through the pump. Sampling was conducted for 2 minutes with approximately 40 gallons (0.2 m^3) of water filtered each minute. Samples were collected in the intake forebay at grate location MTR 1-5 (5 m below the water surface) and from

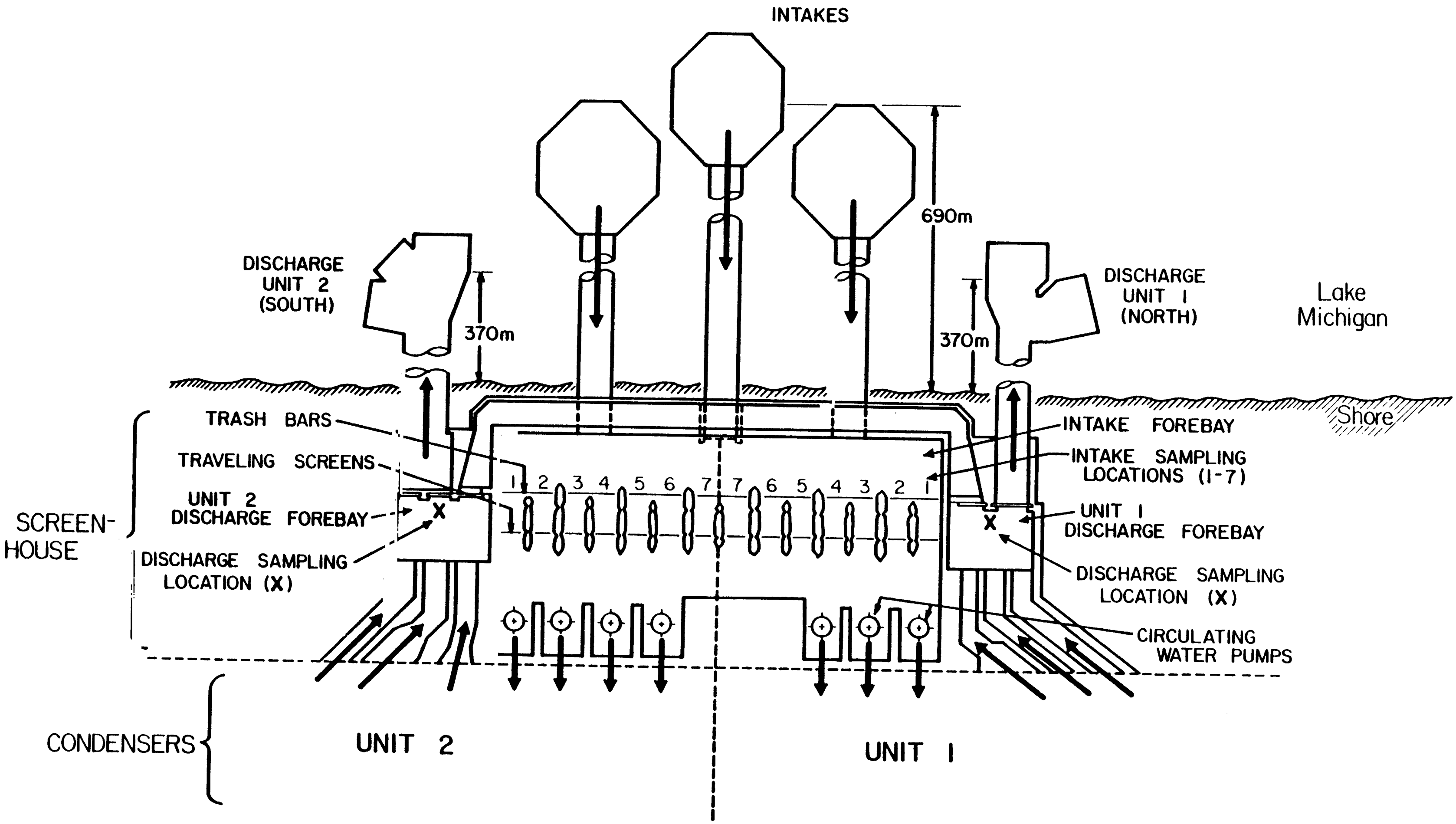

FIG. 42. A schematic view of the condenser cooling water system of the Cook Nuclear Plant.

the discharge forebays of Units 1 and 2 (Fig. 42). Access was limited to a single location in each discharge forebay. Rigid pipes, 7.6 cm in diameter, were mounted in the forebays and were connected by flexible pipes to a sampler. Samples generally were collected within an hour of sunrise.

After sample collection, the mesh carrier was removed from the sampler, the outside washed down with water, and the contents of the plankton bucket transferred to a clean, formalin-free jar. Prior to July 1977, two samples were collected from each intake and discharge location. These replicate samples then were taken to an on-site laboratory where each was subdivided as many times as necessary in a Folsom plankton splitter to give six subsamples, each containing several hundred zooplankton. Two subsamples were immediately examined (0 hour), and the remaining four were each placed in 1-L beakers containing approximately 500 mL of filtered (158 μm) intake water, and maintained at the ambient lake water temperature in a Freas 815 incubator. All incubations were done in the dark. Two subsamples from each sample were examined 6 hours later and the remaining two were examined 24 hours later. Thus, a total of 12 subsamples were examined for each sampling location, representing 4 subsamples at each of 3 incubation times.

Beginning in July 1977, four samples were collected from each intake and discharge location. However, only three subsamples (0 hour, 6 hour, and 24 hour) were obtained from each sample, resulting in the same number of subsamples being examined for each location (12) as with the previous sampling design. Although this change in sampling design did not alter the effort required to examine subsamples, the design change did allow a statistically more efficient examination of the data, including the use of a statistical test that was not possible to apply previously. The Smirnov upper-sided two-sample test,

a non-parametric test (Conover 1971), was employed to examine monthly differences between intake and discharge mortality values.

In the laboratory, each subsample was examined in a circular counting dish under a stereo dissecting microscope. Organisms which exhibited no visceral or appendicular movements even after gentle prodding were classified as "dead." Organisms were identified to suborder (nauplii), genus (Asplanchna spp., immature copepodites), or species (adult copepodites, cladocerans). Dead organisms were placed in a separate vial and preserved with Koechie's fluid. After complete examination of the sample, the remaining live zooplankton were preserved for later examination.

The percentage of dead zooplankton in each intake and discharge sample then was calculated for all zooplankton taxa observed (Appendix Tables 48-96). The average taxa mortality for each sampling location/incubation series was calculated as the weighted mean taxa mortality of the appropriate four replicate values (Appendix Tables 48-96). Use of a weighted mean mortality corresponds to the use of a ratio estimator (Cochran 1977, Raj 1968). Weighted mean mortalities (ratio estimates) are preferred to simple means because samples and subsamples were composed of unequal numbers of zooplankton which were exposed, as groups, to the stresses of collection and laboratory handling (c.f. Cochran 1977). A simple example may clarify the difference between calculating simple and weighted means. Suppose the examination of four replicate samples for a rare species provided the following counts:

Sample 1: 1 out of 4 specimens of this taxon examined were dead;

Sample 2: 1 out of 3 specimens were dead;

Sample 3: 1 out of 1 specimen dead;

Sample 4: 2 out of 2 specimens dead.

The percentage dead in the four samples is 25, 33, 100, and 100%, respectively, and the simple mean percentage dead is (25+33+100+100)/4 = 64.5%. The weighted mean percentage is equal to the total number of animals dead (times 100) divided by the total number examined. In the example, the weighted mean fraction is (1+1+1+2)/(4+3+1+2) = 5/10, corresponding to a weighted mean percentage of 50%. If equal numbers of specimens are examined in each sample, then the simple and weighted mean values are identical.

RESULTS

General Features of the 1977-1978 Mortality Study

Intake-water temperatures during sampling varied from 1°C to over 15°C while discharge temperatures were generally 10C° higher (Fig. 43). In August 1977 discharge temperatures of Unit 1 reached 33°C; in August 1978 temperatures reached 32°C; while in September 1978, discharge water temperatures exceeded 35°C. Discharge water temperatures were less than 30°C in all other months. The plant pumped water at a rate varying from 0.6 to 0.8 x 10^6 gpm (2.3 to 3.0 x 10^3 m^3/min) for Unit 1 and 0.9 to 1.1 x 10^6 gpm (3.4 to 4.2 x 10^3 m^3/min) for Unit 2 during most sampling periods in which units were operating. Lower pumping rates were utilized during the winter and higher rates during the late summer.

Total zooplankton mortalities were highest in January 1978 when they approached (0- and 6-hour incubations) or exceeded 50% (24-hour incubations for Discharge Unit 1, Fig. 44). January 1978 intake and discharge values were statistically similar (Tables 10-12). High mortalities have been observed previously in winter months (Evans *et al*. 1978) in association with resuspension of detrital zooplankton. Total zooplankton discharge mortalities were high

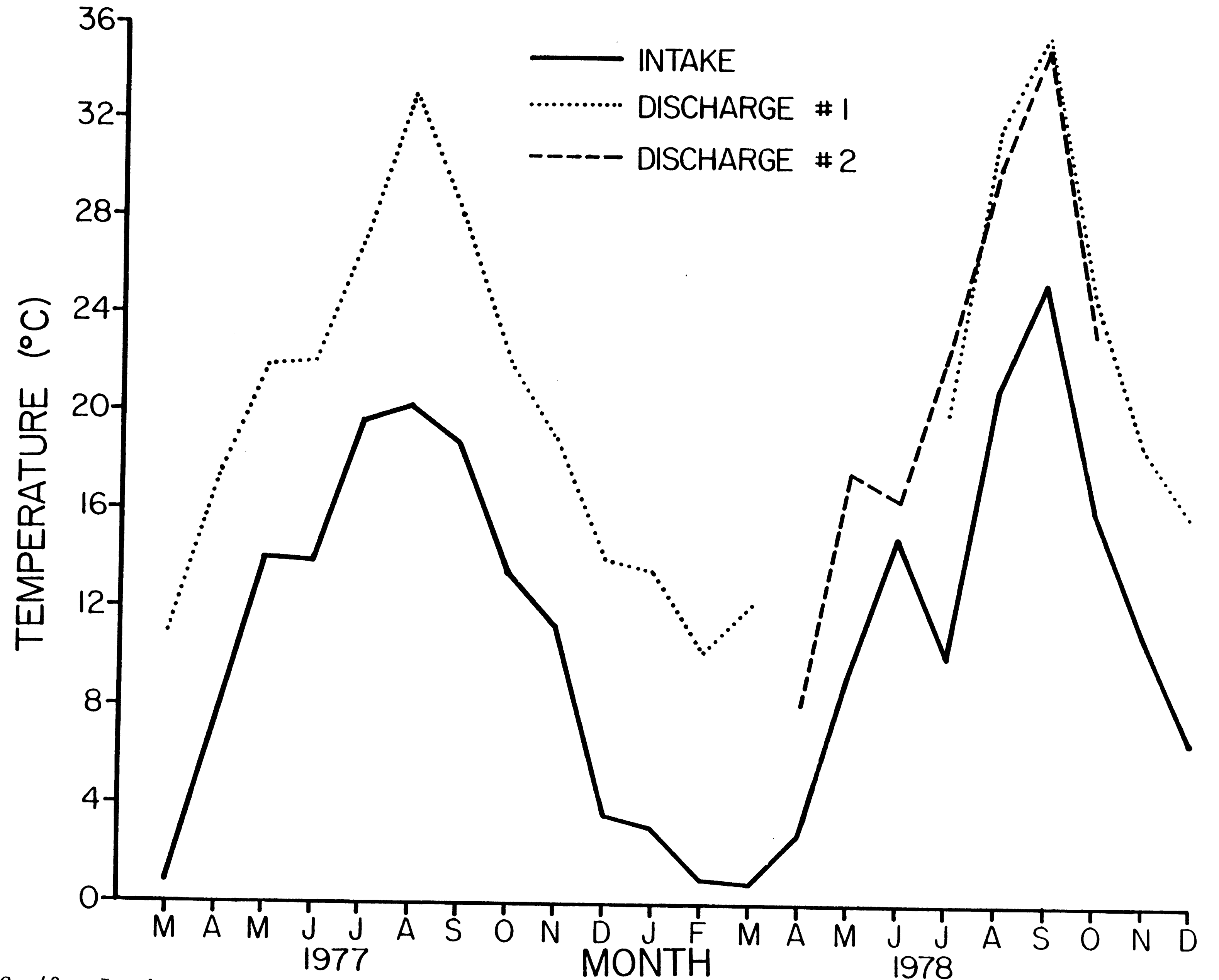

FIG. 43. Intake and discharge water temperatures, 1977-1978.

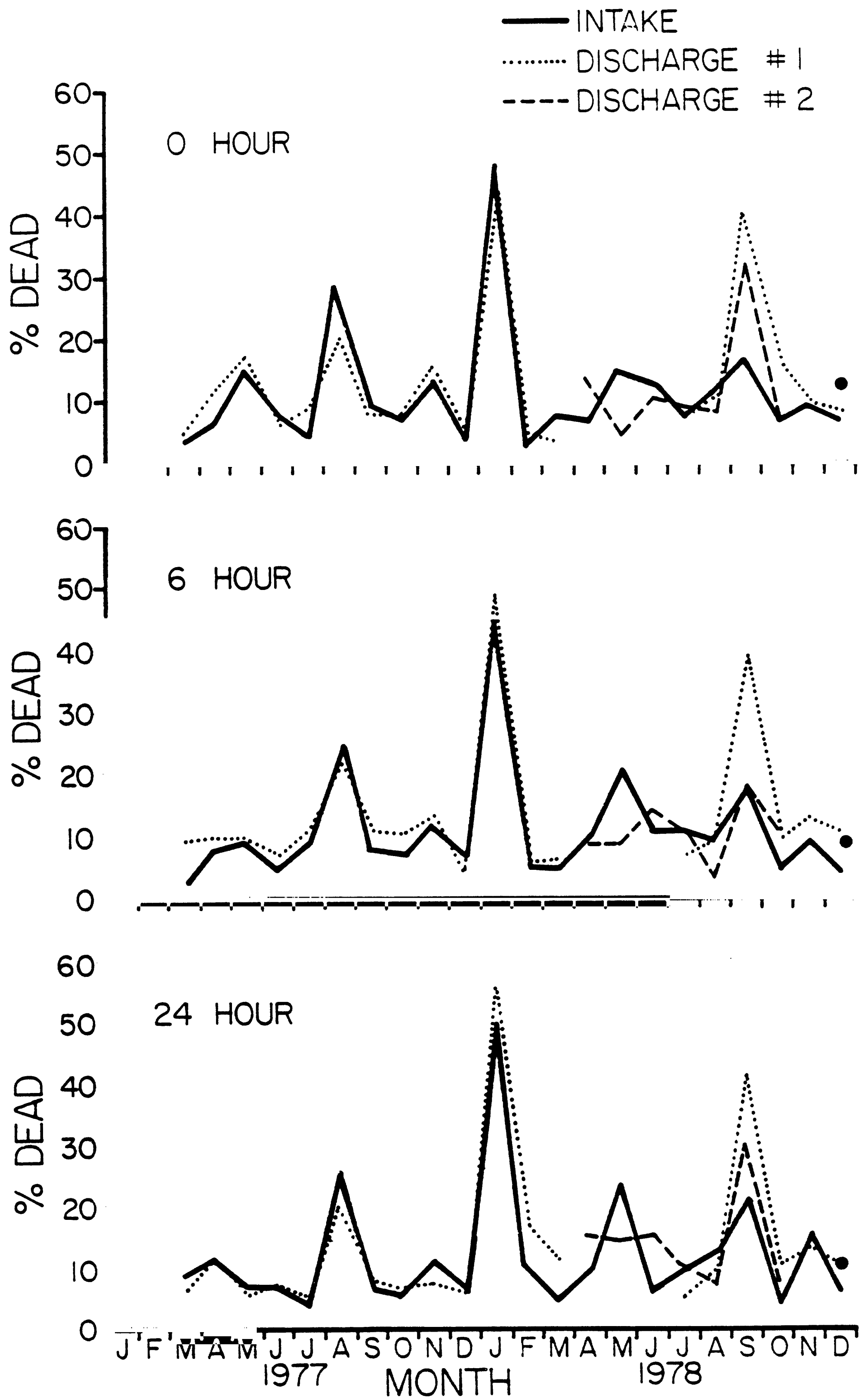

FIG. 44. Monthly mean mortality of total zooplankton at each incubation time. A large dot represents the Discharge 2 value in December 1978.

Table 10. Results of the Smirnov one-sided two-sample tests comparing discharge and intake 0-hour sample mortalities for nine zooplankton taxa categories by month of collection. A -- indicates insufficient data for the test, ns indicates discharge mortalities were not significantly ($p > 0.05$) higher than intake values, and * indicates discharge mortalities were significantly ($p < 0.05$) higher than intake values.

	Month																	
	1977						1978											
	Jy	A	S	O	N	D	J	F	M	A	M	J	Jy	A	S	O	N	D
Copepod nauplii	ns	ns	ns	ns	ns	--	--	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns
Cyclops spp. C1-C5	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cyclops spp. C6	ns	ns	ns	ns	ns	ns	ns	--	ns	ns	ns	ns	ns	*	--	ns	ns	ns
Diaptomus spp. C1-C5	ns	ns	ns	ns	ns	ns	ns	ns	ns	--	ns	ns	ns	*	*	ns	ns	ns
Diaptomus spp. C6	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	--	ns	ns	ns
Bosmina longirostris	ns	ns	ns	ns	ns	--	--	--	--	--	--	ns	ns	ns	ns	ns	ns	ns
Eubosmina coregoni	ns	--	ns	ns	ns	ns	ns	--	--	--	--	--	--	--	*	ns	ns	ns
Daphnia spp.	ns	ns	ns	ns	ns	ns	--	--	--	--	--	ns	ns	ns	ns	ns	ns	ns
Total zooplankton	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Table 11. Results of the Smirnov one-sided two-sample tests comparing discharge and intake 6-hour sample mortalities for nine zooplankton taxa categories by month of collection. A -- indicates insufficient data for the test, ns indicates discharge mortalities were not significantly ($p > 0.05$) higher than intake values, and * indicates discharge mortalities were significantly ($p < 0.05$) higher than intake values.

	Month																	
	1977						1978											
	Jy	A	S	O	N	D	J	F	M	A	M	J	Jy	A	S	O	N	D
Copepod nauplii	ns	ns	ns	ns	ns	--	ns	--	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cyclops spp. C1-C5	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	ns
Cyclops spp. C6	ns	ns	ns	ns	ns	ns	ns	--	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Diaptomus spp. C1-C5	ns	ns	ns	ns	ns	ns	ns	ns	--	--	ns	ns	ns	*	ns	*	*	ns
Diaptomus spp. C6	ns	ns	ns	--	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	--	ns	ns	*
Bosmina longirostris	ns	ns	ns	ns	ns	ns	--	--	--	--	--	ns	ns	ns	ns	ns	ns	ns
Eubosmina coregoni	--	*	ns	ns	ns	ns	ns	--	--	--	--	--	--	--	ns	ns	ns	*
Daphnia spp.	ns	ns	ns	ns	ns	ns	--	--	--	--	--	--	ns	ns	ns	ns	ns	ns
Total zooplankton	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	*

Table 12. Results of the Smirnov one-sided two-sample tests comparing discharge and intake 24-hour sample mortalities for nine zooplankton taxa categories by month of collection. A -- indicates insufficient data for the test, ns indicates discharge mortalities were not significantly ($p > 0.05$) higher than intake values, and * indicates discharge mortalities were significantly ($p < 0.05$) higher than intake values.

	Month 1977						1978											
	Jy	A	S	O	N	D	J	F	M	A	M	J	Jy	A	S	O	N	D
Copepod nauplii	ns	ns	ns	ns	ns	--	--	--	--	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cyclops spp. C1-C5	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cyclops spp. C6	ns	ns	ns	ns	ns	ns	ns	--	--	--	ns	ns	ns	ns	ns	ns	ns	ns
Diaptomus spp. C1-C5	ns	*	ns	ns	ns	ns	ns	ns	--	--	ns	ns	ns	*	ns	*	ns	ns
Diaptomus spp. C6	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Bosmina longirostris	ns	ns	ns	ns	ns	ns	--	--	--	--	ns	ns	ns	ns	ns	ns	ns	ns
Eubosmina coregoni	ns	ns	ns	ns	ns	ns	--	--	--	--	--	--	--	--	ns	ns	ns	ns
Daphnia spp.	ns	ns	ns	ns	ns	ns	--	--	--	--	--	ns	ns	ns	ns	ns	ns	ns
Total zooplankton	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*

during September 1978 sampling (Fig. 44). Discharge Units 1 and 2 mean mortalities averaged 39.5% and 31.6%, respectively, at 0 hours whereas mean intake mortalities averaged 17.5% this month. However, combined Unit 1 and Unit 2 discharge 0-hour mortalities for September 1978 were not significantly higher than intake mortalities (Table 10).

Total zooplankton mortalities were significantly higher in discharge samples than in intake samples in four of the month X incubation comparisons (Tables 11 and 12), none of which occurred for 0-hour incubations. Three occurred at 6 hours (July 1977, October and December 1978) and one at 24 hours (December 1978).

Nauplii 0-hour mortalities (Fig. 45) were generally similar in intake and discharge samples. Although Unit 1 discharge mortalities were considerably higher than intake values in December 1977 and January 1978, these values were based on very limited observations because nauplii were rare in these winter plankton samples (low percent composition values, Fig. 45a). The few observations of nauplii for these 2 months were insufficient to allow the Smirnov two-sample test (one-sided, $p<0.05$) to be applied (Table 10). Discharge mortalities for nauplii were considerably higher than intake mortalities in May and September 1978, but this trend was statistically significant ($p<0.05$) only in September (Table 10).

Immature _Cyclops_ spp. and _Diaptomus_ spp. copepodites exhibited highest 0-hour mortalities in January and September 1978 (Fig. 45). Zero-hour discharge mortalities for immature and adult _Cyclops_ spp. were not significantly ($p<0.05$) greater than intake values in any month (Table 10), although 6-hour incubation mortalities were significantly higher for immature _Cyclops_ spp. in September 1978 discharge samples (Table 11). Immature _Diaptomus_ spp. copepodites had

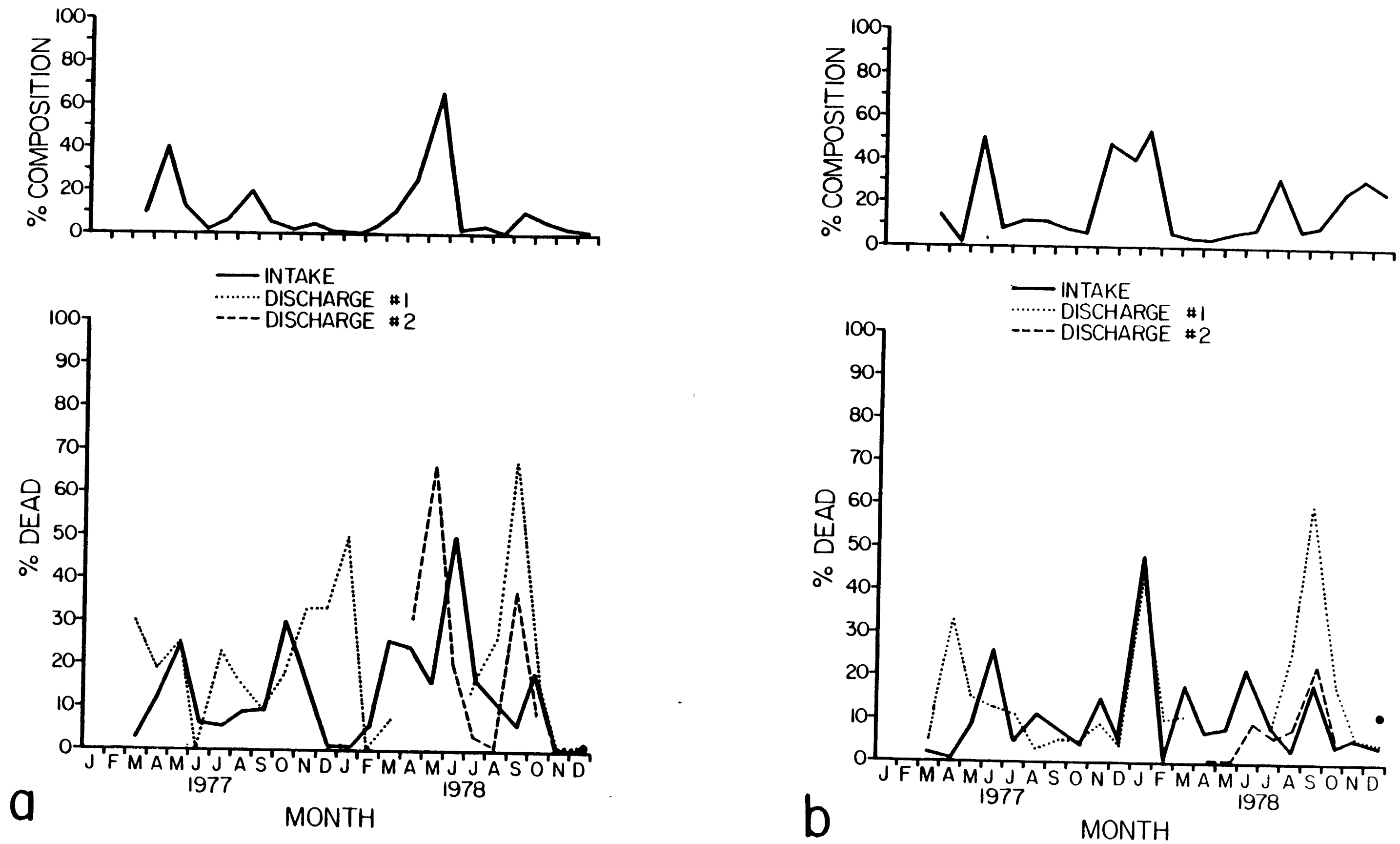

FIG. 45. Monthly mean mortalities (0 hour) for several zooplankton taxa and the mean percent of total zooplankton accounted for by each taxa. A large dot represents the Discharge 2 value in December 1978. a) copepod nauplii, b) <u>Cyclops</u> spp. C1-C5,

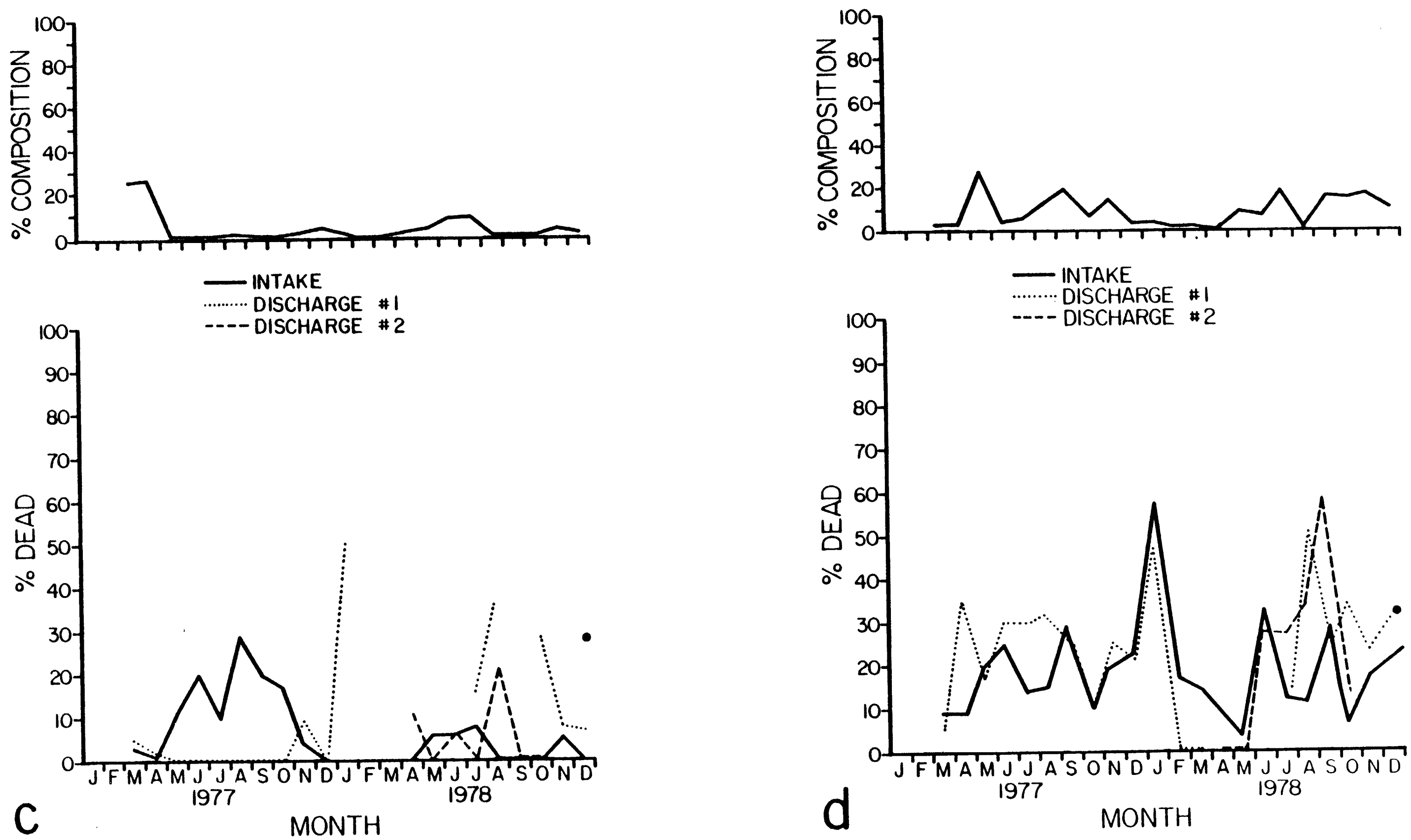

FIG. 45. Continued. c) Cyclops spp. C6, d) Diaptomus spp. C1-C5,

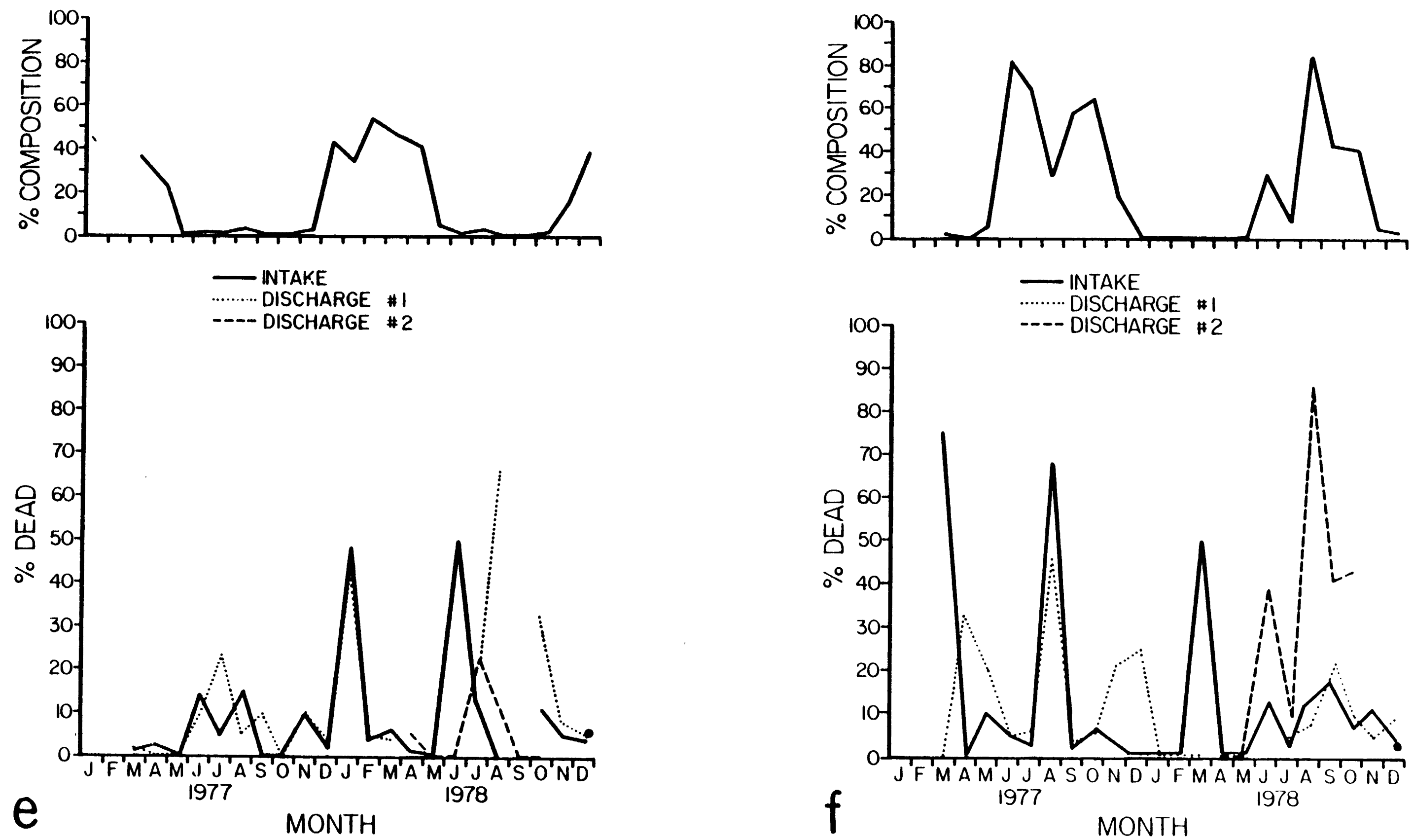

FIG. 45. Continued. e) _Diaptomus_ spp. C6, f) _Bosmina longirostris_,

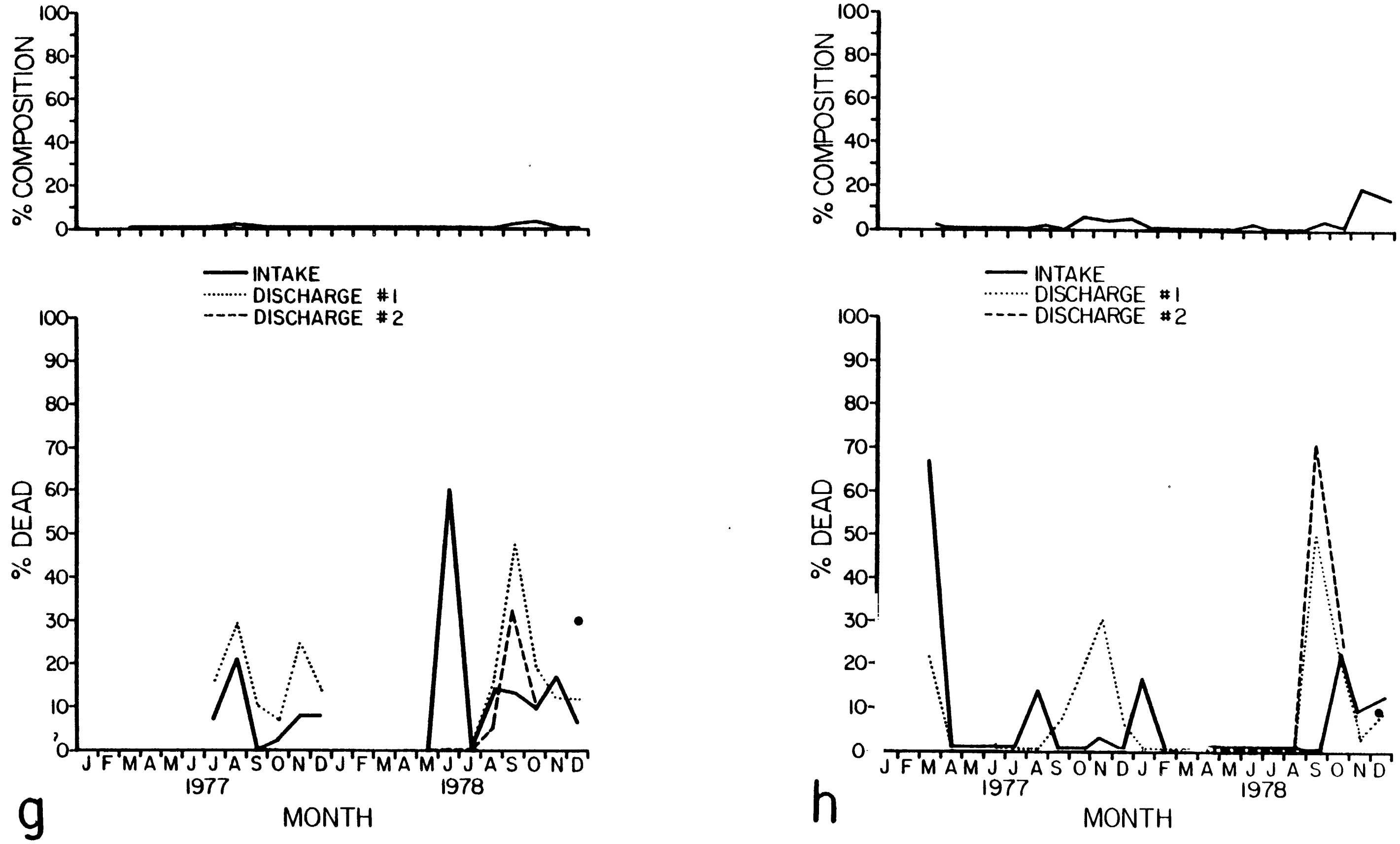

FIG. 45. Concluded. g) Daphnia spp., h) <u>Eubosmina coregoni</u>.

significantly higher discharge mortalities in 8 month X incubation comparisons. All three incubation series for August 1978 had significantly higher discharge mortalities for this taxon. *Diaptomus* spp. adults had significantly higher discharge mortalities only in December 1978 6-hour incubations (Table 11). At other times, when adult *Diaptomus* spp. were abundant, intake and discharge mortalities were similar (Fig. 45).

Zero-hour mortalities for *Bosmina longirostris* varied considerably over the study period (Fig. 45), but never were significantly greater in discharge than in intake samples (Tables 10-12). *Eubosmina coregoni* 0-hour discharge mortalities were significantly higher than intake values only in September 1978. Discharge 6-hour mortalities for this taxon were significantly higher than intake values in August 1977 and December 1978. *Daphnia* spp. accounted for only a small fraction of the animals in the 1977-78 mortality study samples (Fig. 45). The only occasion in which *Daphnia* spp. mortalities were significantly higher in discharge than in intake samples was for the September 1977 6-hour incubations.

Trends in Mortalities over the 1975-1978 Period

Simple mean and weighted mean mortalities for 29 zooplankton taxa are given for the 1975-1978 period in Tables 13-15 for 0-, 6-, and 24-hour incubations of samples from the intake and two discharge locations. Weighted mean values tended to be lower than the corresponding simple means, particularly for rare taxa (e.g., *Limnocalanus macrurus* C6). Total zooplankton weighted mean mortalities ranged from 9.1 to 11.9% over the 45-month period for intake samples and ranged from 10.3 to 14.0% for Unit 1 discharge samples (Tables 13-15). Zooplankton taxa which were relatively abundant (e.g., > 5 percent composition)

Table 13. Mean mortalities over the 1975-1978 period in the 0-hour incubation samples calculated as weighed means ($\bar{x}_w$) and simple means ($\bar{x}_s$) for 29 zooplankton taxa in intake and discharge samples. n is the number of months represented. Mean percent composition values are presented as weighed means (%compl) and as simple means (%comp2).

Taxon	Intake $\bar{x}_w$	Intake $\bar{x}_s$	Intake n	Discharge 1 $\bar{x}_w$	Discharge 1 $\bar{x}_s$	Discharge 1 n	Discharge 2 $\bar{x}_w$	Discharge 2 $\bar{x}_s$	Discharge 2 n	%compl	%comp2
Copepod nauplii	11.4	11.8	45	13.6	16.5	42	13.0	13.5	8	8.7	11.4
Cyclops spp. C1-C5	8.5	9.6	45	9.3	11.8	42	7.9	7.9	8	19.9	21.1
Cyclops bicuspidatus thomasi C6	5.6	10.2	44	7.3	9.1	40	5.0	7.7	8	4.0	5.3
Cyclops vernalis C6	4.5	9.2	20	3.9	6.1	20	5.3	12.5	4	.2	.6
Tropocyclops C1-C5	21.7	25.3	18	11.2	17.5	19	0.	0.	2	.1	.3
Tropocyclops prasinus mexicanus C6	5.4	10.1	28	5.3	7.2	31	0.	0.	3	1.9	2.3
Diaptomus spp. C1-C5	14.1	17.1	45	21.7	23.6	42	25.4	24.2	8	9.2	9.2
Diaptomus ashlandi C6	7.8	14.6	40	8.5	10.2	32	7.3	4.9	6	5.1	9.1
Diaptomus minutus C6	6.2	6.6	41	11.5	13.3	36	5.0	4.2	7	2.1	2.8
Diaptomus oregonensis C6	5.1	10.7	28	7.3	15.6	31	4.8	20.8	5	3.1	3.8
Diaptomus sicilis C6	5.3	11.1	25	5.1	20.2	24	4.8	7.9	6	1.2	3.7
Epischura C1-C5	29.7	35.4	21	22.2	29.2	18	56.0	39.6	3.	.3	.7
Epischura lacustris C6	33.3	31.8	11	23.5	24.5	11	25.0	16.7	3	0.0	.1
Eurytemora C1-C5	7.3	5.7	26	8.5	11.5	24	8.2	9.9	5	1.6	2.4
Eurytemora affinis C6	12.8	14.0	19	10.2	13.7	18	16.7	16.7	2	.2	.5
Limnocalanus C1-C5	17.9	17.9	9	13.3	32.0	12	17.2	69.2	3	.2	2.0
Limnocalanus macrurus C6	2.3	17.3	15	5.0	14.1	12	9.2	18.1	3	1.0	7.8
Bosmina longirostris	8.8	14.1	39	7.8	16.9	37	9.1	12.0	7	26.7	22.8
Ceriodaphnia quadrangula	4.8	2.0	6	19.2	6.9	7	10.2	6.5	3	.1	.9
Chydorus sphaericus	3.1	5.1	18	2.2	2.0	18	3.4	5.2	7	.5	1.8
Daphnia galeata mendotae	11.6	21.4	23	15.6	16.7	22	15.3	33.3	3	.6	1.0
Daphnia retrocurva	18.2	17.9	29	19.0	29.1	30	14.4	12.7	5	2.2	3.0
Diaphanosoma leuchtenbergianum	47.1	44.4	16	41.2	41.0	15	0.	0.	1	.2	.5
Eubosmina coregoni	6.5	13.0	30	7.4	20.8	30	20.9	18.6	6	8.5	9.0
Holopedium gibberum	35.4	46.9	12	31.9	46.8	10			0	.1	.2
Leptodora kindtii	22.6	25.8	11	41.5	38.1	10	25.0	25.0	1	.1	.2
Polyphemus pediculus	26.7	31.3	8	11.1	11.7	6	33.3	33.3	1	.0	.2
Asplanchna spp.	4.2	6.0	30	3.7	4.3	27	5.1	2.0	6	1.9	2.9
Total Zooplankton	9.1	11.4	45	10.3	12.5	42.	10.3	12.6	8.		

Table 14. Mean mortalities over the 1975-1978 period in the 6-hour incubation samples calculated as weighed means ($\overline{x}_w$) and simple means ($\overline{x}_s$) for 29 zooplankton taxa in intake and discharge samples. n is the number of months represented. Mean percent composition values are presented as weighed means (%comp1) and as simple means (%comp2).

Taxon	Intake $\overline{x}_w$	Intake $\overline{x}_s$	Intake n	Discharge 1 $\overline{x}_w$	Discharge 1 $\overline{x}_s$	Discharge 1 n	Discharge 2 $\overline{x}_w$	Discharge 2 $\overline{x}_s$	Discharge 2 n	%comp1	%comp2
Copepod nauplii	11.9	11.6	43	14.7	18.0	41	11.2	10.1	8	7.9	11.3
Cyclops spp. C1-C5	8.7	8.9	44	10.1	11.8	41	6.5	10.6	8	19.9	20.7
Cyclops bicuspidatus thomasi C6	6.8	12.4	44	8.1	10.5	40	14.5	13.0	8	4.0	5.3
Cyclops vernalis C6	4.0	1.4	22	6.5	7.0	20	14.8	12.1	3	.2	.6
Tropocyclops C1-C5	6.1	7.1	18	19.0	25.5	14	0.	0.	2	.2	.4
Tropocyclops prasinus mexicanus C6	6.2	14.0	27	8.1	11.4	29	13.0	14.6	3	2.2	2.4
Diaptomus spp. C1-C5	15.7	19.0	44	23.8	24.8	41	22.3	16.8	8	9.2	9.5
Diaptomus ashlandi C6	7.5	9.5	38	11.4	9.2	34	7.2	3.2	7	5.0	9.4
Diaptomus minutus C6	8.1	9.8	38	13.1	18.4	37	5.7	7.8	6	1.7	2.6
Diaptomus oregonensis C6	3.1	9.1	31	5.5	13.9	25	5.1	9.2	4	2.7	2.9
Diaptomus sicilis C6	7.0	15.9	21	6.4	14.6	23	3.0	30.6	5	1.3	4.6
Epischura C1-C5	17.7	13.7	19	31.5	32.9	22	36.4	25.4	3	.3	.8
Epischura lacustris C6	43.8	40.0	10	29.4	34.6	13	0.	0.	1	0.	.1
Eurytemora C1-C5	7.4	5.1	25	9.5	8.4	23	8.3	10.5	5	1.5	2.3
Eurytemora affinis C6	6.0	9.4	17	7.4	15.7	17	5.9	20.0	5	.1	.4
Limnocalanus C1-C5	22.0	37.7	11	25.0	40.7	8	30.3	60.7	3	.3	2.1
Limnocalanus macrurus C6	2.9	10.1	14	7.1	22.3	14	7.2	35.9	3	1.1	9.0
Bosmina longirostris	9.0	17.6	36	9.7	13.2	36	4.6	8.2	7	27.3	24.3
Ceriodaphnia quadrangula	4.8	2.5	7	14.6	8.9	6	3.3	2.7	3	.1	1.2
Chydorus sphaericus	3.2	3.3	22	1.7	2.3	19	1.3	6.8	5	.5	1.3
Daphnia galeata mendotae	12.6	19.3	23	15.6	20.1	22	7.1	14.6	6	.7	1.2
Daphnia retrocurva	21.9	25.0	28	24.9	24.4	26	13.0	11.3	6	2.6	3.5
Diaphanosoma leuchtenbergianum	57.4	59.1	16	67.8	69.9	12	50.0	50.0	2	.3	.5
Eubosmina coregoni	7.2	9.7	26	11.1	13.3	31	11.8	10.9	5	9.2	9.8
Holopedium gibberum	35.4	42.7	7	39.7	51.1	9			0	.1	.4
Leptodora kindtii	70.6	76.8	11	67.3	60.9	11	75.0	50.0	2	.1	.2
Polyphemus pediculus	20.0	25.0	6	53.8	55.3	7	0.	0.	1	.0	.3
Asplanchna spp.	6.9	6.4	25	8.1	10.2	27	9.5	4.8	3	1.3	2.8
Total Zooplankton	9.7	10.9	44.	12.2	13.3	41.	7.1	10.6	8		

Table 15. Mean mortalities over the 1975-1978 period in the 24-hour incubation samples calculated as weighed means ($\bar{x}_w$) and simple means ($\bar{x}_s$) for 29 zooplankton taxa in intake and discharge samples. n is the number of months represented. Mean percent composition values are presented as weighed means (%comp1) and as simple means (%comp2).

Taxon	Intake $\bar{x}_w$	Intake $\bar{x}_s$	Intake n	Discharge 1 $\bar{x}_w$	Discharge 1 $\bar{x}_s$	Discharge 1 n	Discharge 2 $\bar{x}_w$	Discharge 2 $\bar{x}_s$	Discharge 2 n	%comp1	%comp2
Copepod nauplii	16.4	10.9	45	17.1	11.9	42	12.7	13.7	8	6.6	8.8
Cyclops spp. C1-C5	10.3	11.2	45	12.0	11.9	42	6.8	13.6	8	19.1	20.7
Cyclops bicuspidatus thomasi C6	8.6	15.1	45	10.8	15.9	40	13.8	29.2	8	3.9	5.5
Cyclops vernalis C6	4.2	14.8	18	6.1	10.1	20	0.	0.	5	.3	.8
Tropocyclops C1-C5	12.5	11.4	10	6.9	7.4	16	0.	0.	3	.1	.3
Tropocyclops prasinus mexicanus C6	5.9	8.9	31	9.2	8.1	29	5.0	2.1	3	2.3	2.3
Diaptomus spp. C1-C5	15.5	20.1	45	23.1	25.5	42	23.0	18.8	8	9.0	9.4
Diaptomus ashlandi C6	13.4	12.0	39	17.8	19.4	35	13.3	4.6	7	5.1	10.1
Diaptomus minutus C6	14.0	15.3	41	22.9	19.8	36	8.9	16.4	8	2.2	2.9
Diaptomus oregonensis C6	7.1	15.4	35	11.9	14.1	29	0.	0.	2	3.3	3.3
Diaptomus sicilis C6	8.8	15.8	23	11.5	21.6	22	11.6	29.8	5	1.2	4.7
Epischura C1-C5	21.9	28.7	20	29.9	29.4	19	27.8	26.0	5	.3	.7
Epischura lacustris C6	26.7	31.8	11	31.6	31.8	11	20.0	25.0	4	.0	.1
Eurytemora C1-C5	13.8	16.1	25	19.8	15.5	25	9.8	8.8	6	1.3	1.9
Eurytemora affinis C6	14.4	19.7	21	10.1	11.1	17	15.8	5.4	4	.2	.5
Limnocalanus C1-C5	29.5	37.7	12	22.1	22.3	9	53.5	51.8	2	.3	2.0
Limnocalanus macrurus C6	5.4	10.9	12	4.5	14.8	14	8.3	32.7	3	1.0	11.7
Bosmina longirostris	11.0	13.9	37	9.6	11.5	37	9.7	13.1	7	28.5	25.0
Ceriodaphnia quadrangula	11.3	6.8	6	22.7	21.9	7	8.9	6.4	3	.1	1.5
Chydorus sphaericus	4.0	12.0	22	3.3	11.3	20	3.6	3.8	6	.6	1.6
Daphnia galeata mendotae	15.7	25.1	26	15.7	22.3	23	17.5	37.3	5	.6	1.1
Daphnia retrocurva	28.2	27.8	30	27.3	24.6	27	19.6	24.2	6	2.4	3.2
Diaphanosoma leuchtenbergianum	49.2	52.8	14	65.2	63.4	11	100.0	100.0	1	.1	.3
Eubosmina coregoni	9.9	10.7	29	15.5	24.0	27	18.8	18.9	5	9.3	8.7
Holopedium gibberum	28.0	52.0	6	66.1	65.3	7			0	.1	.2
Leptodora kindtii	70.0	64.3	10	74.2	63.4	8	100.0	100.0	1	.1	.2
Polyphemus pediculus	15.0	21.2	8	15.4	21.9	8	14.3	33.3	3	.0	.2
Asplanchna spp.	9.9	10.9	29	12.6	14.7	25	13.4	6.6	4	1.7	2.6
Total Zooplankton	11.9	14.1	45	14.0	15.2	42	11.2	14.6	8		

in the samples generally had weighted mean mortalities less than 15% (Tables 13-15). Four very rare cladoceran species, *Diaphanosoma leuchtenbergianum*, *Holopedium gibberum*, *Leptodora kindtii*, and *Polyphemus pediculus* had the highest mortalities. *Leptodora kindtii* has a large and fragile body that is particularly subject to mechanical damage.

Results of statistical tests to examine differences in zooplankton taxa mortalities between Unit 1 intake and discharge samples over the 42-month operational period are shown in Table 16. The upper-sided median test, a non-parametric procedure, was used (c.f. Evans *et al*. 1978). Mortalities were not significantly ($p<0.05$) higher for discharge samples, compared to intake samples, for any taxa observed in the 24-hour incubations (Table 16). For the 0- and 6-hour incubations, calanoid copepod categories were the main taxa exhibiting significantly higher discharge mortalities, although *Daphnia* spp. and *Eubosmina coregoni* also exhibited significant differences. The mean monthly difference between intake and discharge Unit 1 mortalities for taxa which exhibited significant differences ranged between 2.6 and 7.3% (Table 16).

Further investigations were undertaken to determine the relationship between zooplankton mortality, water temperature, and ΔT. Zero-hour discharge mortalities for total zooplankton were not significantly ($p<0.05$) correlated with either intake or discharge water temperatures. Also, discharge mortalities were not significantly correlated to ΔT's for the 1975-1978 study period. The difference between Unit 1 discharge and intake monthly mortality means was significantly correlated ($r = 0.31$, $n = 42$, $p<0.05$) with intake water temperature but not with Unit 1 discharge water temperature ($r = 0.26$, $n = 42$, $p>0.05$). The difference between Unit 2 discharge and intake mean mortalities was not significantly correlated with intake temperature ($r = 0.21$, $n = 8$, $p>0.05$) nor with Unit 2 discharge water temperature ($r = 0.23$, $n = 8$, $p>0.05$),

Table 16. Zooplankton taxa for which Discharge #1 mortalities were significantly higher than intake mortalities over the 1975-1978 period as determined by the upper-sided median test. Intake and discharge values from a month were used only if both values were based on the observation of at least ten animals. n is the number of monthly pairs of values examined, p is the attained level of significance, and $\bar{d}$ is the mean monthly difference in mortalities, Discharge #1 minus intake.

Incubation	Taxon	n	p	$\bar{d}$
0-hr.	*Diaptomus minutus* C6	21	0.038	3.1%
	Daphnia retrocurva	17	0.025	5.3%
6-hr.	Copepod nauplii	33	0.012	3.4%
	Cyclops spp. C1-C5	40	0.003	3.5%
	Diaptomus ashlandi C6	20	0.006	3.4%
	Diaptomus minutus C6	16	0.010	6.5%
	Diaptomus oregonensis C6	11	0.006	4.7%
	Daphnia galeata	8	0.035	7.3%
	Eubosmina coregoni	15	0.004	5.2%
	Major Zooplankton Category Results			
0-hr.	Calanoids C1-C6	42	0.010	5.5%
	Calanoids C1-C5	39	0.012	6.7%
	Diaptomus spp. C1-C6	41	0.014	6.4%
	Daphnia spp.	20	0.021	3.6%
6-hr.	Calanoids C1-C6	41	<0.001	6.4%
	Calanoids C1-C5	39	<0.001	6.4%
	Diaptomus spp. C1-C6	40	0.008	6.1%
	Diaptomus spp. C6	29	0.012	4.2%
	Total Zooplankton	41	<0.001	2.6%

although these relationships are represented by a limited number of observations (7 months).

DISCUSSION

The results of the mortality studies suggest that plant passage is lethal to only a small percent of the zooplankton which pass through its cooling

system. The mean 0-hour mortalities for total zooplankton in the intake (9.1%) and discharge (10.3%) waters are similar to mortality estimates obtained for the first 23 months of this study (Evans et al. 1978) and to estimates from other power plant studies on Lake Michigan (Industrial Bio-Test Laboratories, Inc. 1975, Wetzel 1975, Limnetics, Inc. 1975 and 1976).

Intake mortalities generally were low, with exceptions in August 1977 and January 1978 when 0-hour intake mortalities exceeded 28%. High intake mortalities occurred in August 1977 when mortalities of the abundant cladoceran Bosmina longirostris exceeded 68%. Cladocerans frequently become trapped at the surface of experimental beakers by air bubbles under their carapace. These air bubbles probably stress cladocerans (Nebeker 1976) and contribute to the high cladoceran intake mortality observed.

High intake mortalities were observed in January 1978; similarly high mortalities were observed in January 1976. Intake water temperatures averaged 3.1°C and 2.8°C respectively, indicating the plant was not recirculating water at this time. The cause of high winter intake mortalities is not known. During these colder months of the year, dead zooplankton probably require longer periods of time to exhibit physical signs of decay than at higher temperatures (Wheeler 1967). Thus, many of the zooplankton enumerated as freshly killed may have been dead prior to sample collection. Storms may resuspend dead zooplankton from the sediments and contribute additional sources of apparent intake mortality. It is interesting to note that zooplankton populations declined in both January studies from December abundance values. For example, zooplankton densities decreased from $17{,}025/m^3$ in the intake waters in December 1977 to $2{,}009/m^3$ in January 1978. Such zooplankton possibly were in a weakened

condition and more susceptible to the stresses encountered during sample collection than zooplankton collected at other times of the year.

Zooplankton mortalities generally were statistically similar in intake and discharge waters at the three incubation times. At 0 hours, discharge mortalities were significantly greater than intake mortalities only in August 1978 (for *Cyclops* spp. adults and immature *Diaptomus* spp. copepodites) and in September 1978 (for nauplii, immature *Diaptomus* spp. copepodites, and *Eubosmina coregoni*). Discharge water temperatures exceeded 31°C on these two occasions. Kreuger (1974) determined that *Diaptomus* spp. acclimated to 20°C are stressed by short-term exposures (minutes) to temperatures in the mid-thirties. *Cyclops* spp., while more tolerant, also are stressed by these temperatures.

It is more difficult to evaluate the results of the 6-hour and 24-hour incubations as individual taxa are not isolated. It is probable that a significant amount of predation occurs in these beakers and that some dead zooplankton are consumed. However, the data do suggest *Diaptomus* spp. copepodites were stressed in August 1977 and 1978 and in September 1978 when discharge water temperatures exceeded 30°C.

At the genus or species level, there was no evidence of increasing mortality with increasing discharge water temperature while such temperatures remained below 30°C. Furthermore, there was no evidence of increasing mortality with increasing Δ-T. These data suggest that as long as the plant continues to operate with Δ-T's of 12C° or less and at discharge-water temperatures below 30°C, zooplankton mortalities will remain low. It is only at higher discharge water temperatures and Δ-T's that zooplankton mortalities become high (Davies and Jensen 1974, Limnetics, Inc. 1975, Brauer *et al*. 1974, Drost-Hansen 1969).

The power plant chlorinated the cooling waters infrequently in 1977 and 1978 and has since ceased to use this biocide. Thus, chlorination effects are not addressed in this report.

There are several ways to estimate the percent of zooplankton killed by plant passage. One way is to use the results of the statistical analyses. According to these tests, differences between total zooplankton mortalities in the discharge and intake waters were statistically significant only in the 6-hour incubations, suggesting that zooplankton were not immediately killed during plant passage. However, several abundant taxa had mortalities which were significantly higher in the discharge 0-hour incubations than in intake samples. For example, Diaptomus spp. copepodites (C1-C6) had a 1975-1978 average difference in mortalities between discharge and intake of 6.4% for 0-hour incubations. As this category composed an average of 20.7% of the zooplankton passing through the plant, this suggests that on average at least 1.3% of the zooplankton passing through the plant were killed each month.

Another way to estimate the mean mortality of total zooplankton at 0 hours is to subtract the mean mortality of animals in the intake waters (9.1%) from the mean mortality of zooplankton in the discharge waters (10.3%). The resulting value, 1.2%, is an estimate of the percent of total zooplankton which were immediately killed by plant passage. If it is assumed that all of the dead zooplankton observed in the intake samples were dead as they entered the plant's intake, and do not represent deaths due to our collection and laboratory handling procedures, then a correction is appropriate. The calculation can be corrected by subtracting the mean mortality from 100, dividing the mean discharge mortality minus the mean intake mortality by this difference, and multiplying the quotient by 100: [(10.3-9.1) X 100] / (100-9.1) = 1.32%. A

similar approach was used by Davies and Jensen (1974) to calculate a corrected estimate of zooplankton motility resulting from plant passage. The resulting value, 1.32%, is larger than the uncorrected estimate and will increase compared to the uncorrected value as the percentage dead in the intake increases. Nevertheless, the mortality studies do indicate that immediate zooplankton mortalities as a direct result of plant passage are low under current operating conditions.

SECTION 4

NUMBERS AND BIOMASS OF ZOOPLANKTON PASSING THROUGH THE POWER PLANT

INTRODUCTION

The entrainment program, in addition to estimating the percent of zooplankton killed by plant passage, also determines the concentration of zooplankton passing through the plant. This information has several applications. First, by knowing the rate at which the plant withdraws water from the lake and associated zooplankton concentrations, estimates can be made of the numbers of zooplankton passing through the plant. Similarly, by estimating zooplankton mortality immediately resulting from plant passage, estimates can be made of the number of zooplankton killed by plant passage. Calculations also can be expressed in terms of biomass.

Comparisons of zooplankton population characteristics in the cooling waters with population characteristics in the nearshore region provide an indication of the representativeness of the plant as a zooplankton sampler. For example, are zooplankton populations in the cooling waters strongly dominated by epibenthic forms? If so, this suggests that the plant withdraws a significant proportion of its water from the deeper regions of the water column. The zooplankton community, as characterized by the lake survey program, thus would be less susceptible to entrainment damage than the results of the mortality studies would suggest.

The entrainment program provides an opportunity to obtain more detailed information on zooplankton population dynamics in the nearshore region than is economically feasible with the lake survey program. Entrainment sampling avoids high ship costs and provides an opportunity for biweekly, weekly, or daily

sampling with few logistical constraints. Such information potentially can provide more precise estimates of the temporal characteristics of zooplankton variability in the nearshore region. Furthermore, winter sampling is feasible with entrainment sampling while the lake survey program is restricted to the April to November or December period. Great Lakes studies documenting long-term changes and recent recoveries in phytoplankton populations have relied heavily on intake sampling (Damann 1960, Davis 1964, Nicholls *et al*. 1977, Danforth and Ginsberg 1980). However, similar studies have not been conducted for zooplankton.

MATERIALS AND METHODS

Entrainment Abundance Estimates

Zooplankton were collected once a month from the intake (MTR 1-5) and discharge (Units 1 and 2) forebays. Two 5-minute replicate samples were taken at each station at four sampling times: noon, sunset, midnight, and sunrise. Sampling at the four times helped to account for patchiness and diel differences in the vertical distribution of zooplankton. Samples were simultaneously collected from the intake and discharges. Hale diaphragm pumps were used to draw water from the forebay and pass it through a 30-cm, 158 μm aperture net (Fig. 46). Each net was suspended in a barrel of water to help minimize damage to the animals. The volume of water filtered was measured with a flowmeter located in the outflow pipe.

Sixteen samples (2 locations x 4 times x 2 replicates) were collected each month between February 1977 to February 1978 when Unit 2 became operational. After that, when both units were operating, 24 samples were collected (3 locations x 4 times x 2 replicates). When just one unit was operating, the

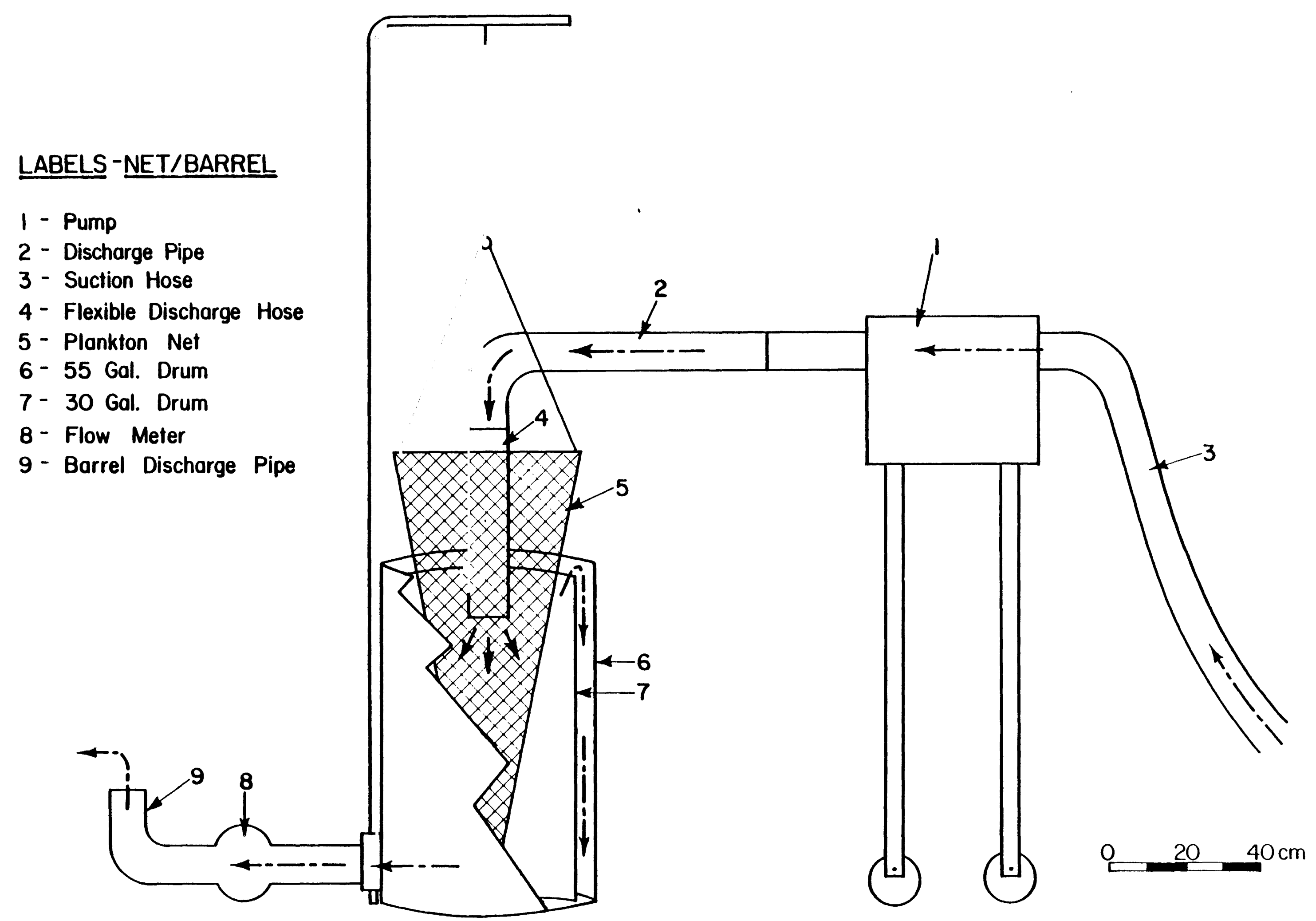

FIG. 46. Pump and net arrangement for zooplankton entrainment abundance samples.

intake forebay and the discharge forebay of the operational unit were sampled (16 samples total). To provide more detailed information on zooplankton population dynamics, additional samples were collected at noon and midnight at weekly or biweekly intervals during some months. All samples were examined by the same methods as described in Section 1. Station mean and summary data are in the Appendix (Tables 97-150).

Heterogeneity Study

The sampling program was designed to investigate whether there were differences in abundances of zooplankton at different intake grates and discharge pipes of the two units or at different depths within the intake forebay. This study was part of the plant's Technical Specifications, which required a determination of heterogeneity in the forebay with both units operating. A heterogeneity study previously had been conducted for Unit 1 (Evans 1975). The two-unit study was conducted between 14:24 and 16:05 EDT on 14 September 1978.

In addition to the two fixed pipes used to sample the discharge waters of Units 1 and 2, four sampling locations were chosen in the intake forebay. Two intake locations were on the Unit 1 side of the screenhouse, one in front of travelling screen MTR 1-1 and the other in front of travelling screen MTR 1-5. The other two intake locations were on the Unit 2 side in front of travelling screens MTR 2-1 and MTR 2-5. In this report, these locations are referred to as grates MTR 1-1, MTR 1-5, MTR 2-1, and MTR 2-5.

Two replicate samples were collected at 0.6, 5.5, and 8.5 m below the water surface in the intake forebay. The discharge sampling pipes had a fixed water depth of 5.5 m. Samples were taken simultaneously from all six locations for

each of six times. The first two sample sets had intake depths of 0.6 m, the next two replicates were from an intake forebay depth of 5.5 m, and the last two sample sets were from an intake depth of 8.5 m. A total of 36 samples were collected and later enumerated for zooplankton species abundances and composition using the procedure outlined in Section 1.

Two approaches were used to examine the data. A two-way analysis of variance for factorial design (California Biomedical Series Program BMD8V implemented on the Michigan Terminal System) was employed separately for the intake and discharge data. Grates (4) and depths (3) were the two variables of interest for the intake data. Because depth could not be varied for the discharge samples, pipes (2) and time (3) were the two factors of interest for the discharge data. The sampling interval between replicates was 10 minutes while the interval between the three designated "times" was 30 minutes. Thus, the "time" variable in the analysis of the discharge data would not be expected to show significant differences between "times" as compared to differences between replicates unless there were large changes in the abundances of animals in the discharge waters over the 101-minute period of the study. In this sense, the inclusion of the time variable in the analysis of the discharge data was intended only to act as a crude control for the depth factor in the intake two-way analysis.

The second analytical approach employed one-way analyses of variance to examine differences between sampling locations for any of the depth/time sets. *A priori* tests were also conducted to determine if the discharge samples differed in abundance from intake samples.

Abundance data were transformed to logarithms ($y = \log(\#/m^3+1)$) before analysis. The percentage composition data were transformed using the inverse-

sine square root transformation (Steel and Torrie 1960). Residuals from the analysis of variance were examined and found to meet satisfactorily the assumptions of the statistical models.

All data were analyzed in order to determine whether total numbers of zooplankton or particular species were heterogeneously distributed between sampling sets. Zooplankton of a variety of shapes, sizes, and swimming abilities were analyzed (Evans 1975, p. 100).

RESULTS

Seasonal Concentration of the Major Zooplankton Taxa in the Cooling Waters and in the Inshore Region

To determine seasonal patterns in abundance and composition of the major zooplankton taxa in the cooling waters, their mean concentrations were calculated each month. The results (Fig. 47) were obtained by averaging the abundances of the major taxa in the intake samples from the four sample times (eight samples). To compare the zooplankton entrained with those in the water column overlying the intakes, field survey data were used to estimate the mean concentrations of the major zooplankton taxa near the intakes (Fig. 47). Estimates were obtained by averaging zooplankton abundances at all stations within the 10-m depth contour. This included 7 or 13 stations (14 or 26 samples) depending on the cruise. Lake currents transport water several kilometers per day (Ayers *et al*. 1967) so a few stations not in the immediate intake area were included to provide a better estimate of zooplankton populations during the 16 to 19 hours of the entrainment study. Cruises were usually conducted one day after the entrainment study.

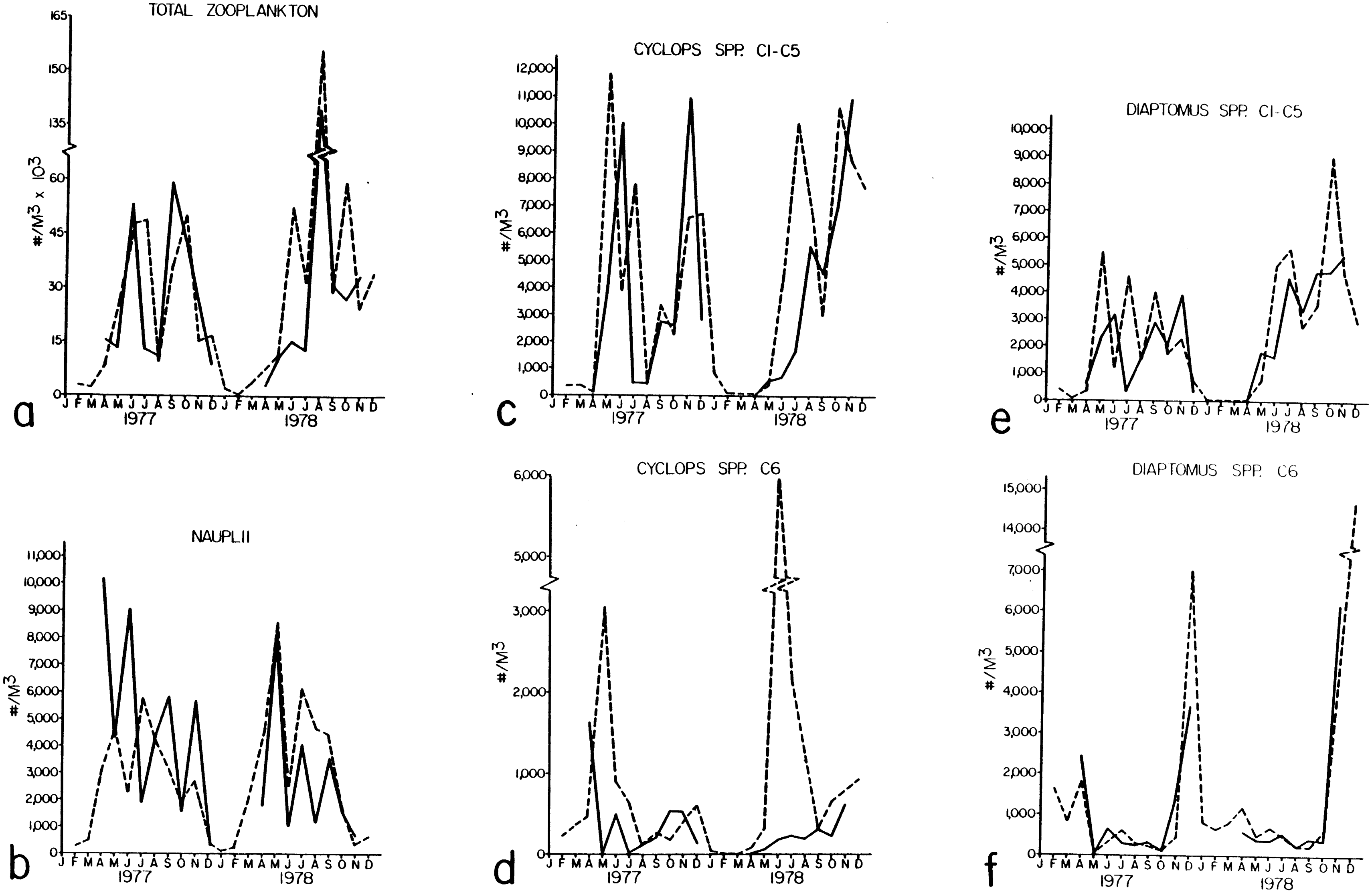

FIG. 47. Graphical comparisons of zooplankton densities in the entrainment abundance samples (dotted line) and in the inshore zone (solid line). Entrainment data points represent the mean of up to four sampling times (sunset, midnight, sunrise, and noon) and inshore zone points represent the mean of up to 13 stations in the 5-10 m depth zone. a) Total zooplankton, b) copepod nauplii, c) <u>Cyclops</u> spp. C1-C5, d) <u>Cyclops</u> spp. C6, e) <u>Diaptomus</u> spp. C1-C5, f) <u>Diaptomus</u> spp. C6,

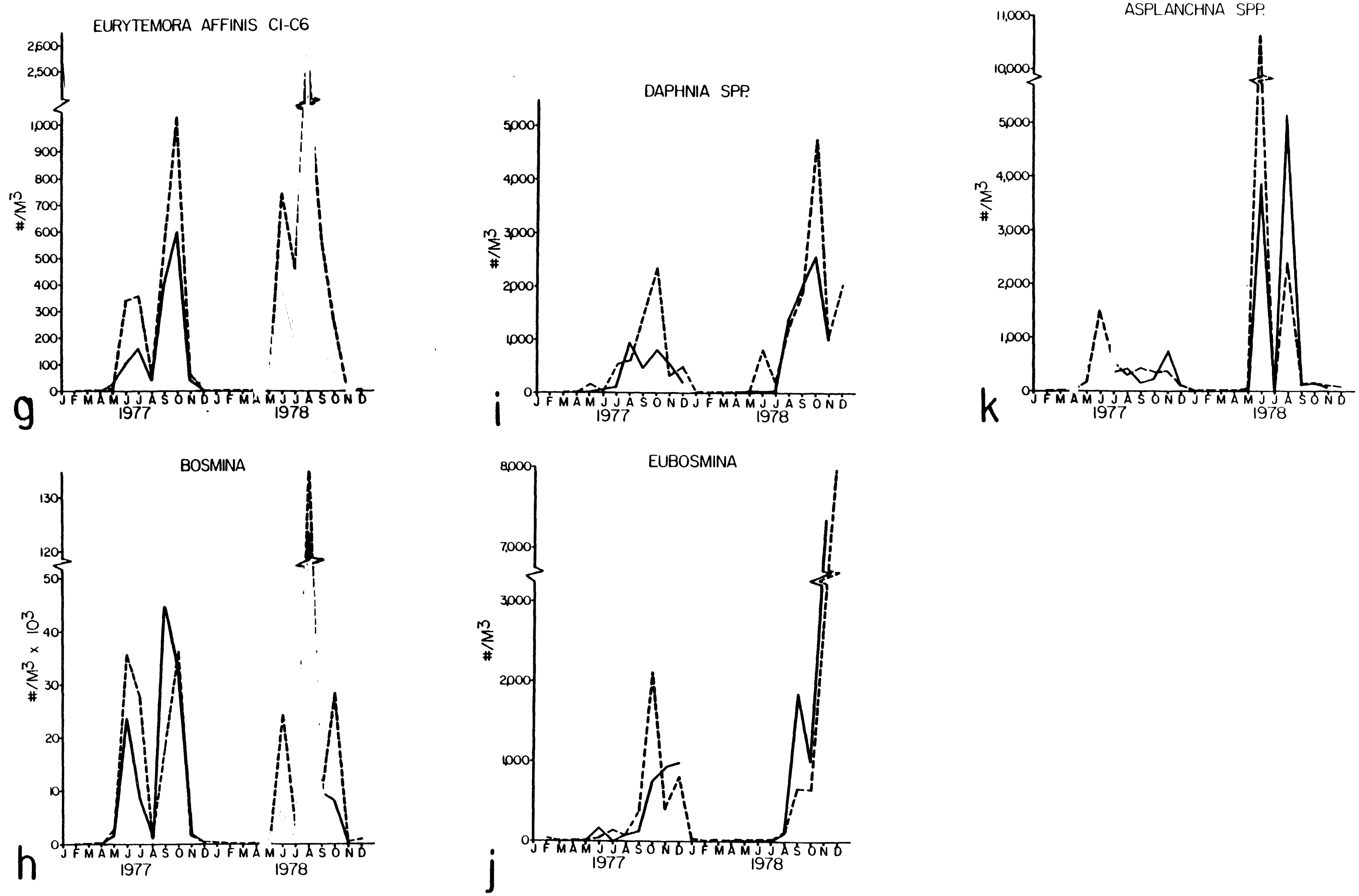

FIG. 47. Concluded. g) Eurytemora affinis C1-C6, h) Bosmina longirostris, i) Daphnia spp., j) Eubosmina coregini, k) Asplanchna spp.

In addition to graphical comparisons, major taxa mean densities in entrainment and inshore field survey samples also were examined by calculating correlation coefficients, by testing the significance of differences in densities using the median test, and by calculating the geometric mean ratio of inshore/entrainment monthly mean densities (Table 17).

Generally, zooplankton occurred in similar concentrations in the inshore and entrainment waters (Fig. 47) and correlations between mean densities in the two sets of samples were highly significant (Table 17). Adult *Cyclops* spp. was the only taxon which had a low and nonsignificant correlation ($r = 0.16$, $p>0.05$). The median test indicated that mean densities of *Cyclops* spp. adults were significantly ($p<0.01$) more abundant in entrainment samples. The geometric mean of the ratio of inshore:entrainment densities (Rg) was the smallest observed, Rg = 0.3, and indicates these cyclopoids were approximately three times more abundant in the entrainment samples than in inshore field survey samples. This difference in densities for *Cyclops* spp. adults appears to be partly a result of its epibenthic distribution (discussed below) and the difficulty of obtaining accurate density estimates for this taxon in the inshore waters because of its rarity there. Although other epibenthic taxa, such as *Cyclops* spp. C1-C5 and *Eurytemora affinis* C1-C6, tended to be more abundant in entrainment samples, as evidenced by Rg values less than 1.0 (Table 17), these trends were not statistically significant. *Eubosmina coregoni* had statistically ($p<0.01$) higher abundances in inshore field survey samples, but the overall magnitude of these differences was small (Rg = 1.2). Nauplii, *Tropocyclops prasinus mexicanus* C1-C6, *Diaptomus* spp. C6, *Epischura lacustris* C1-C6, and *Asplanchna* spp. also tended to be slightly more abundant in field survey inshore samples (by factors less than two), but none of these trends were statistically

Table 17. Comparison of density data for selected zooplankton taxa from entrainment abundance and inshore field survey samples. Correlation coefficients (r) their significance, significance of the median test (M), and the geometric mean of the ratio of densities (field survey/entrainment) for n = 32 sampling dates during 1975-1978.
ns indicates not significantly different at p <0.05
* indicates significance at the 0.05 level, and
** at the 0.01 level

	75-78 r	75-78 M	75-78 Rg
Copepod nauplii	.50 **	ns	1.7
Immature Cyclopoids	.47 **	ns	0.8
Cyclops spp. C6	.16	**	0.3
Tropocyclops prasinus mexicanus C1-C6	.82 **	ns	1.2
Diaptomus spp. C1-C5	.59 **	ns	1.0
Diaptomus spp. C6	.88 **	ns	1.2
Epischura lacustris C1-C6	.83 **	ns	1.4
Eurytemora affinis C1-C6	.87 **	ns	0.8
Limnocalanus macrurus C1-C6	.92 **	ns	0.5
Bosmina longirostris	.88 **	ns	1.0
Daphnia spp.	.91 **	ns	0.7
Eubosmina coregoni	.93 **	**	1.2
Asplanchna spp.	.64 **	ns	1.6
Total Zooplankton	.82 **	ns	0.9

significant (Table 17). There was no evidence that larger zooplankton were under-represented in entrainment samples, suggesting that there was little avoidance by zooplankton of the sampling pump's intake. The high intake flow and the use of a large volume pump minimize this potential problem.

Samples taken between regular sampling times revealed information on zooplankton population dynamics. More frequent sampling showed large variations

in zooplankton abundances (Fig. 48). These variations were especially noticeable in the summer months of 1977 and 1978 when samples were collected weekly. Concentrations changed as much as twelvefold in one week. These weekly fluctuations were more pronounced in the immature forms (nauplii, immature *Cyclops* spp., and immature *Diaptomus* spp. copepodites) which could be a result of short zooplankton generation times which occur in the summer and can cause rapid population shifts. Abundances did not seem to vary as much in the cooler months although samples were collected less frequently.

Epibenthic and Benthic Copepods and Cladocerans

Epibenthic and benthic copepods and cladocerans rarely were collected in the lake or entrainment samples. Moreover, taxa concentrations were generally much higher in entrainment samples (Fig. 49). This was true even for the relatively abundant taxa such as *Cyclops vernalis*, *Cyclops bicuspidatus thomasi*, and *Chydorus sphaericus*. For most taxa, the seasonal patterns of lake and entrainment concentrations did not match, often because the lake concentrations were much lower than entrainment ones and probably provided imprecise population estimates. *Eurytemora affinis* was an exception as it was relatively abundant in both lake and entrainment samples and the seasonal trends in abundance for lake and entrainment matched closely.

Although benthic and epibenthic zooplankton were not abundant, their concentrations were underestimated because neither sampling scheme (lake or entrainment) adequately sampled the sediment-water interface which they inhabit. In the lake survey, the plankton nets did not sample the bottom meter of the water column. It was unlikely that many epibenthic and benthic species were drawn into the plant except during storms as the openings of the intake pipes

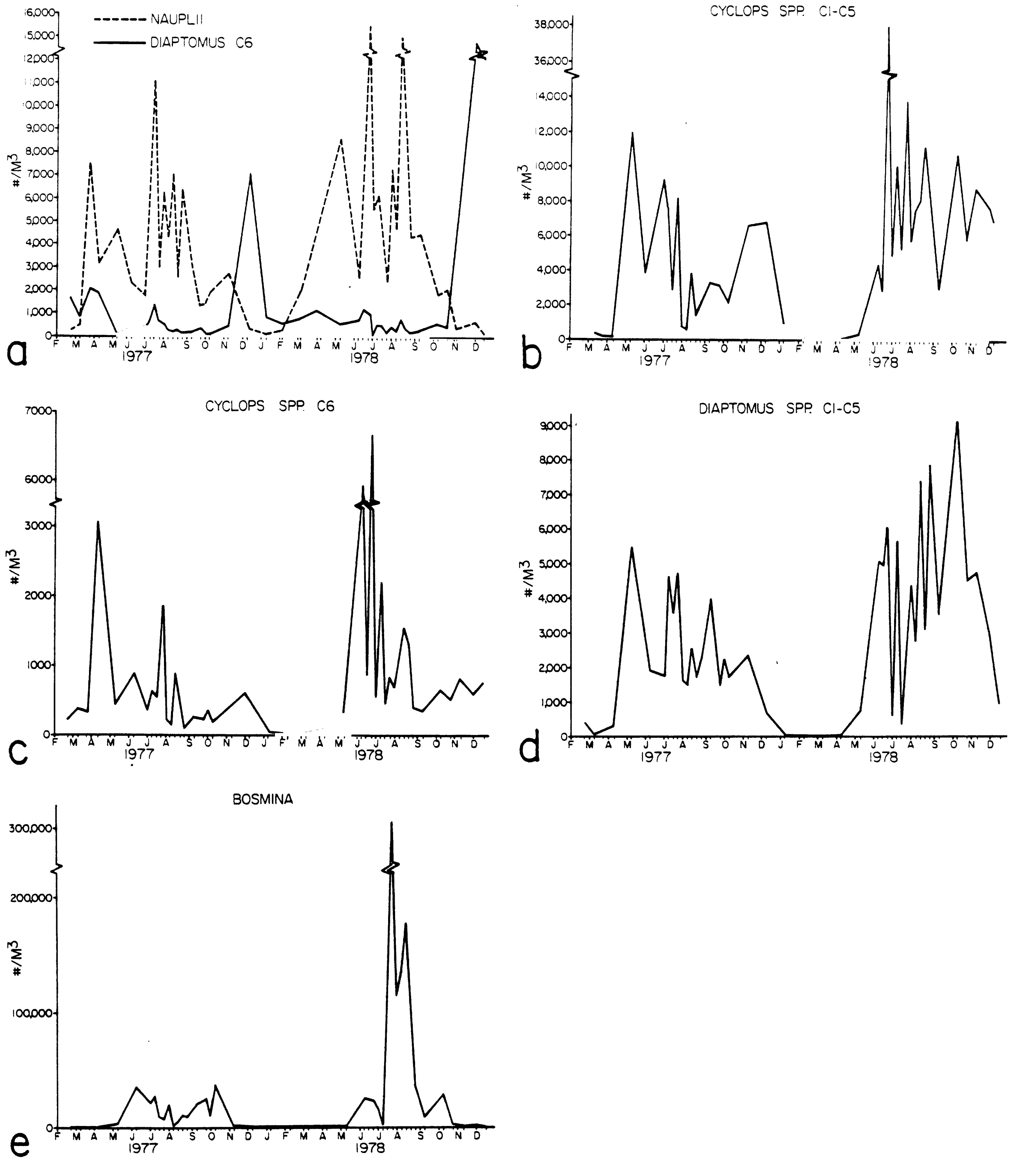

FIG. 48. Variation in abundance of selected zooplankton taxa collected in entrainment abundance samples. Samples were collected at noon and midnight at weekly or bimonthly intervals. a) copepod nauplii and Diaptomus spp. C6, b) Cyclops spp. C1-C5, c) Cyclops spp. C6, d) Diaptomus spp. C1-C5, e) Bosmina longirostris.

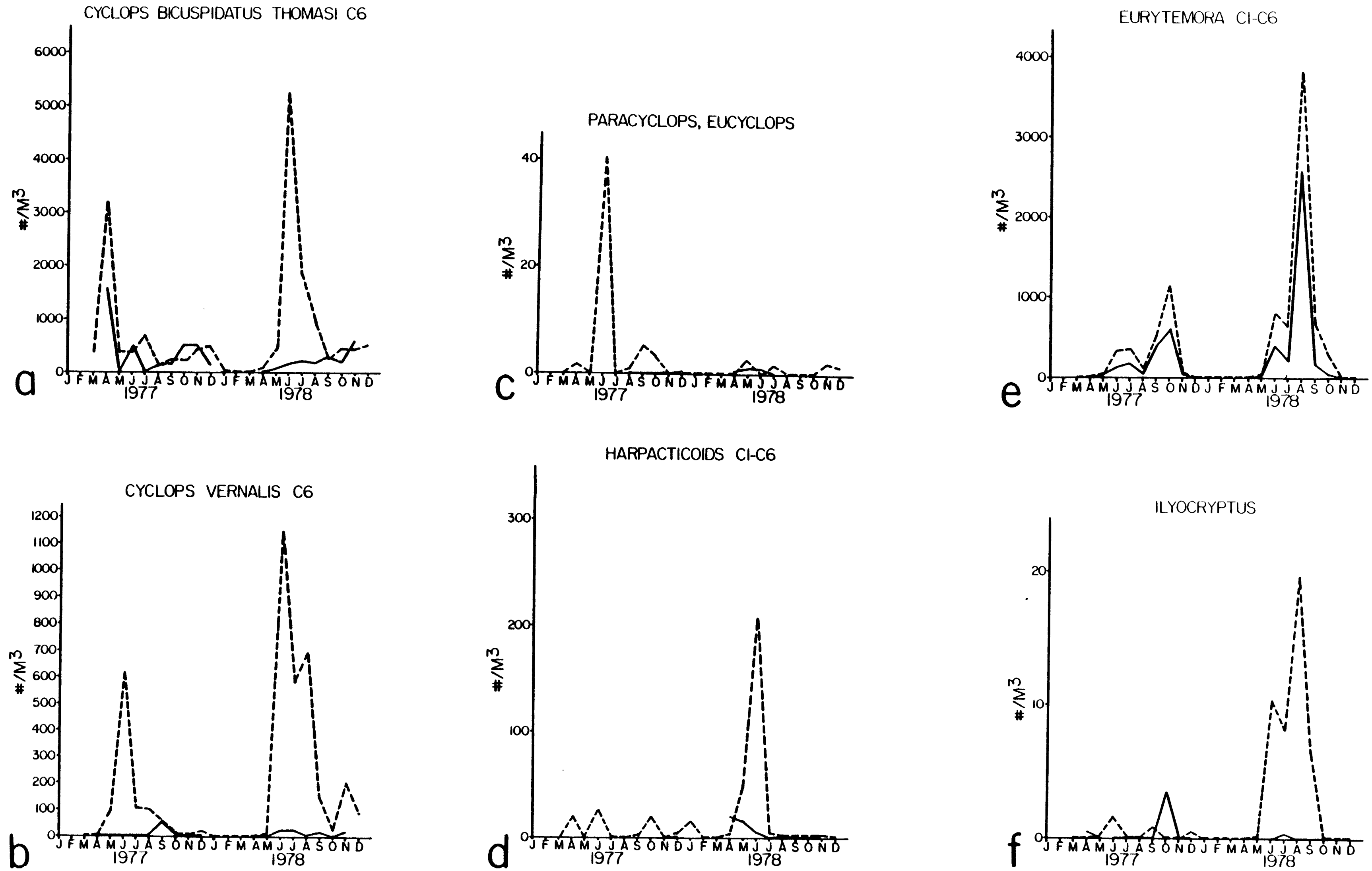

FIG. 49. Seasonal abundance of epibenthic zooplankton collected in the entrainment abundance samples (dotted line) and in field survey samples from the 5- to 10-m depth zone (solid line).
a) Cyclops bicuspidatus thomasi, b) Cyclops vernalis, c) Paracyclops spp. and Eucyclops spp. C1-C6, d) harpacticoid copepods C1-C6, e) Eurytemora affinis C1-C6, f) Ilyocryptus spp.,

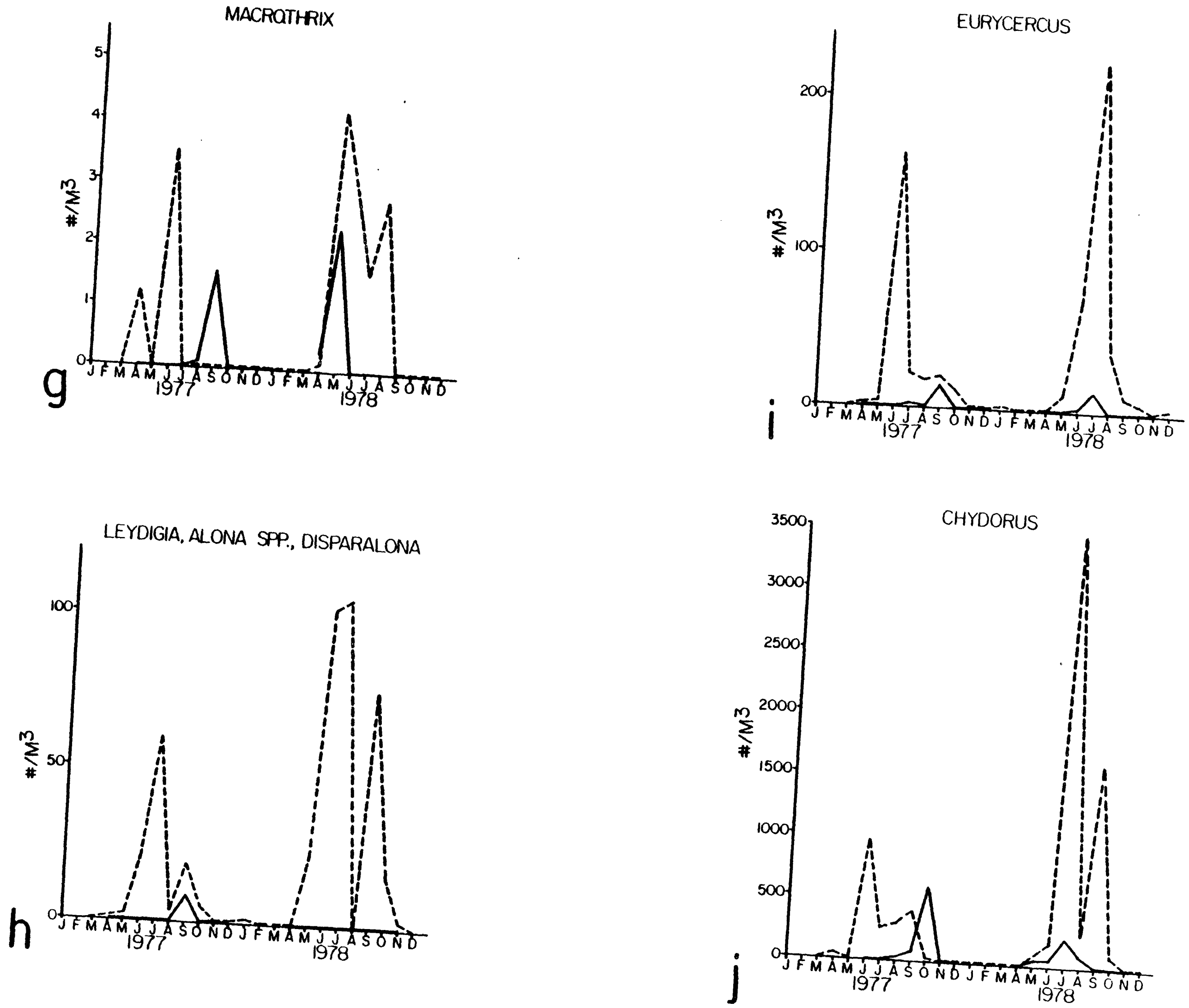

FIG. 49. Concluded. g) Macrothrix spp., h) Leydigia and Alona and Disparalona spp., i) Eurycercus lamellatus, j) Chydorus sphaericus.

are 1 m above the bottom. Variability in storm events may account for the discrepancy between intake and lake seasonal dynamics with a storm occurring during one study but not during the other. Similarly, epibenthic zooplankton may enter the water column more frequently at some times than others, e.g., during mating, dispersal when population levels are high or food limiting, etc.

Numbers and Biomass of Zooplankton Passing Through the Power Plant and the Estimated Maximum Losses

Billions of zooplankton passed through the plant each month (Fig. 50). The number entrained ranged from 16 x 10^9 in February 1978 to 49,712 x 10^9 in August 1978 and averaged 5,899 x 10^9. More zooplankton passed through the plant during the summer and autumn months when zooplankton populations were largest. Three times as many zooplankton were taken into the plant in 1978 than in 1977. This was partly because twice as much water was circulated in 1978 after Unit 2 became operational in February 1978. Another factor was that zooplankton population levels were higher in 1978 than in 1977. Maximum loss estimates assumed that immediate (0 hour) discharge mortality represents maximum losses of zooplankton in the vicinity of the discharge jets. The actual loss probably was lower (Section 2). This conservative approach is utilized because our study does not estimate additional mortalities inflicted on zooplankton when they are discharged at high velocities into the lake.

The seasonal pattern of the number of zooplankton entrained (Fig. 50) did not match the biomass pattern of entrained zooplankton (Fig. 51). This was mainly because in the winter months, when fewer animals were entrained, they tended to be larger, more mature forms such as adult *Diaptomus* spp. and the later copepodite stages of *Cyclops bicuspidatus thomasi*. Estimated biomass

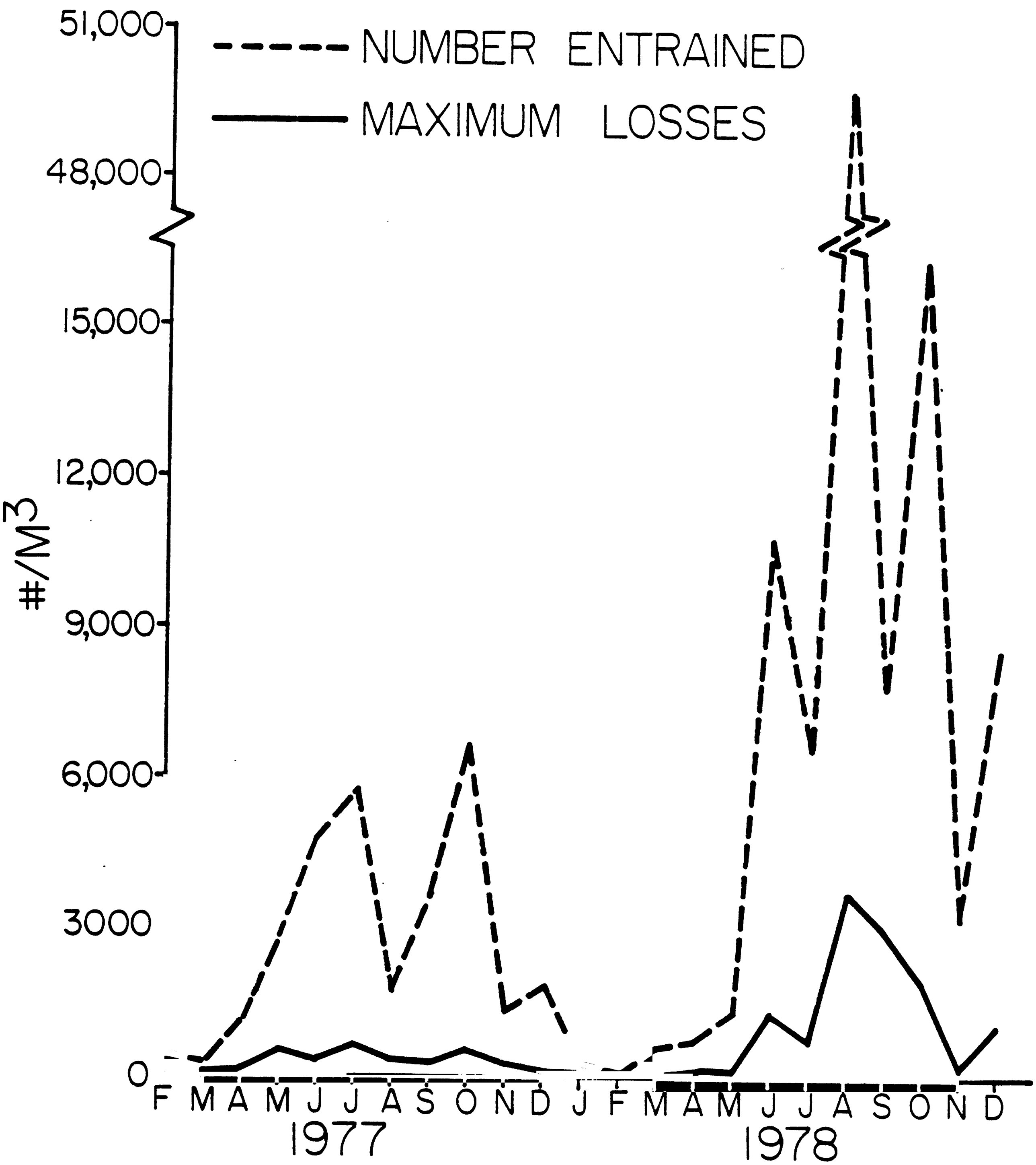

FIG. 50. Estimates of the number of zooplankton entrained and the maximum numbers lost during 1977 and 1978.

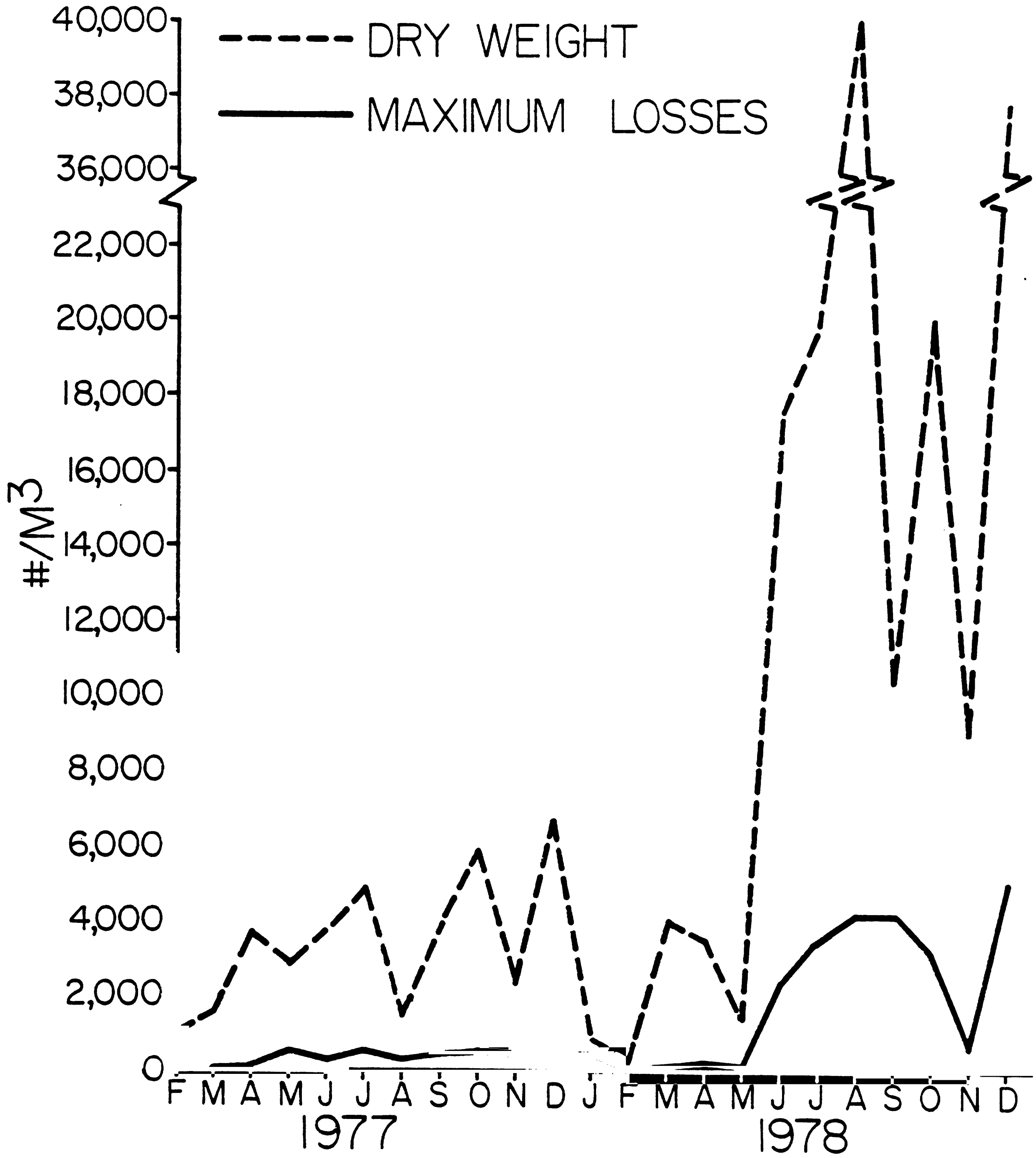

FIG. 51. Estimates of dry weight of entrained zooplankton and maximum losses during 1977 and 1978.

through the plant ranged from 109 kg dry wt/month (February 1978) to 39,718 kg dry wt/month (August 1978) and averaged 8,819 kg dry wt/month (194,251 lb fresh wt). Maximum biomass loss estimates ranged from 11 kg dry wt/month (February 1978) to 5,021 kg dry wt/month (December 1978) and averaged 1,232 kg dry wt/month (27,137 lb fresh wt). From February 1977 through December 1978, a maximum of 14% of the biomass of zooplankton that passed through the plant was killed before being discharged back into the lake. This compares with 10.3% of the zooplankton by numbers and suggests a preferential mortality of heavier zooplankton.

Heterogeneity Study

Figures 52 and 53 show the mean densities of the 15 zooplankton taxa analyzed at the six sampling locations and the three depth/time sets. Results of the two-way analysis of variance for the intake data are presented in Tables 18 and 19. Neither the intake abundance data nor the percentage composition data showed any significant ($p<0.05$) interaction between grate and depth factors. *Daphnia retrocurva* was the only taxon which exhibited significant differences between depths in both abundance and percentage composition. The mean densities of *D. retrocurva* were greatest at the 0.6-m depth for all four intake grates (Fig. 53). Nauplii, adult *Tropocyclops prasinus mexicanus*, immature *Diaptomus* spp. copepodites, and *Daphnia retrocurva* all exhibited significant differences between intake grates in both abundance and percentage composition.

Results of the two-way analysis of variance for the discharge data are presented in Tables 20 and 21. A significant interaction between location and time was found only for the *Tropocyclops prasinus mexicanus* abundance data.

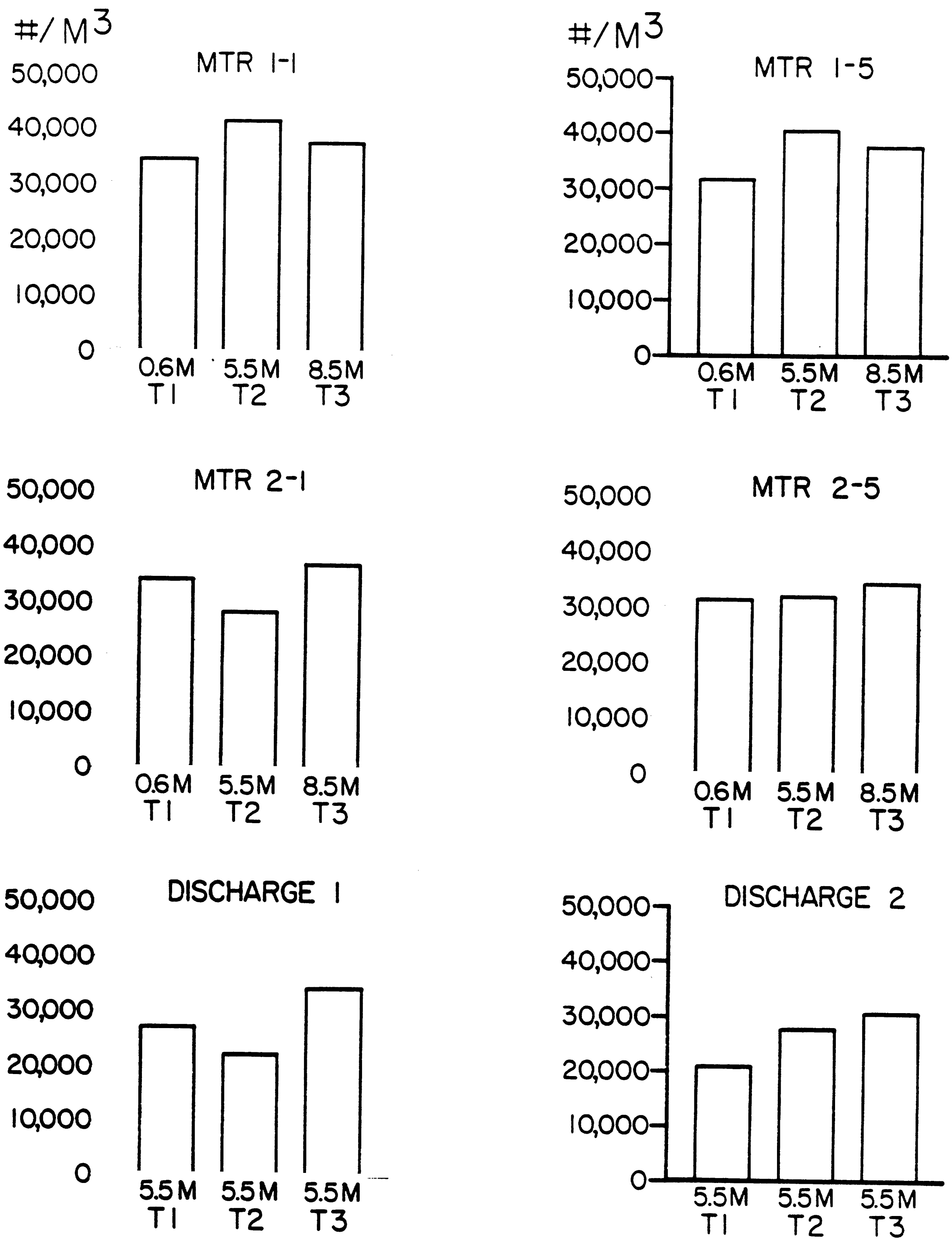

FIG. 52. Mean concentration (numbers/m^3) of total zooplankton at six locations for each of three depths (intake forebay locations) or times (discharge forebays). T1, T2, and ~~T3~~ T3 denote the first, second, and third sampling times, respectively.

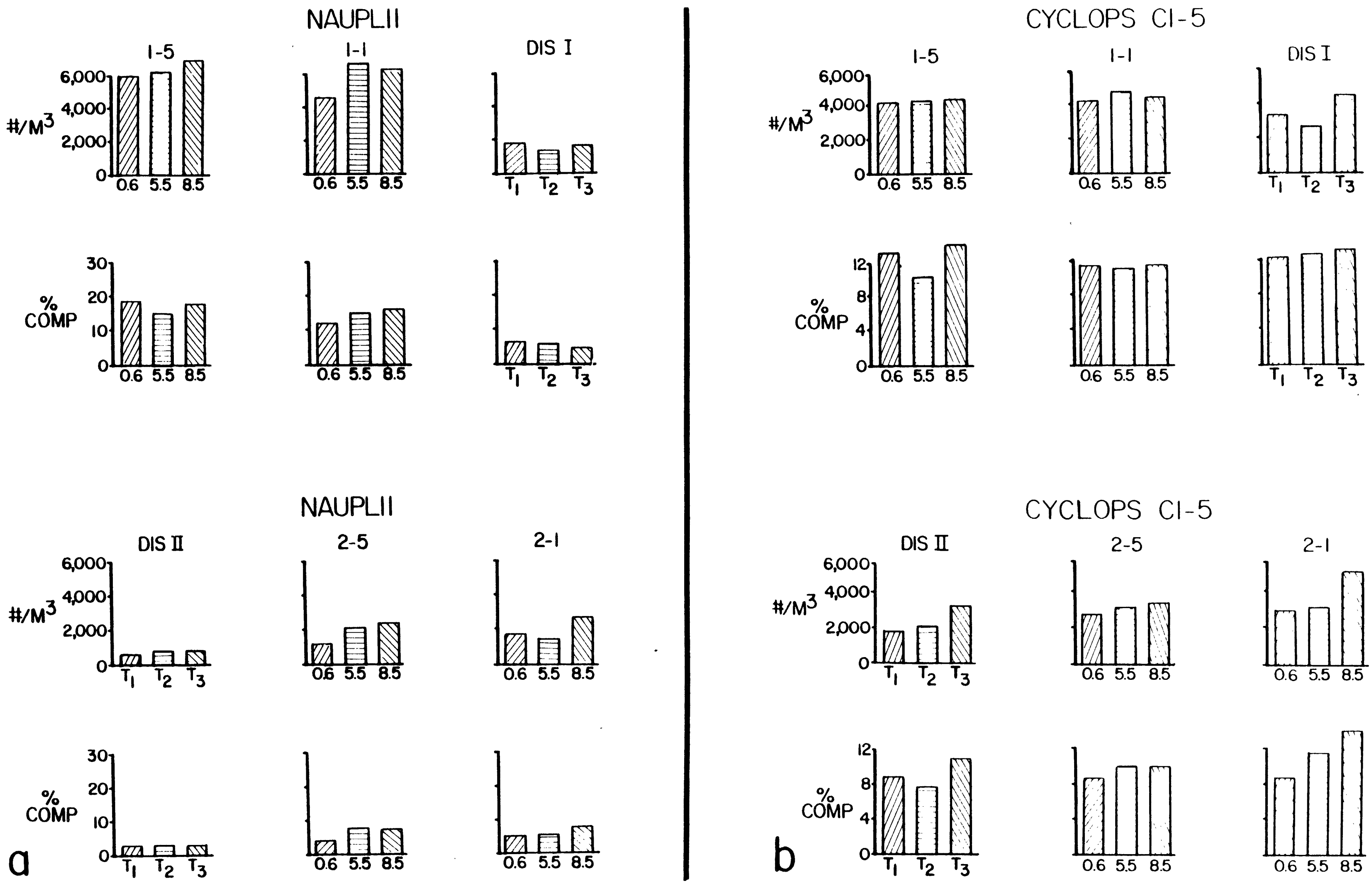

FIG. 53. Mean concentration (numbers/m^3) and percent composition of selected zooplankton taxa at six locations for each of three depths (intake forebay locations) or times (discharge forebays). T1, T2, and T3 denote the first, second, and third sampling times, respectively. a) copepod nauplii, b) <u>Cyclops</u> spp. C1-C5,

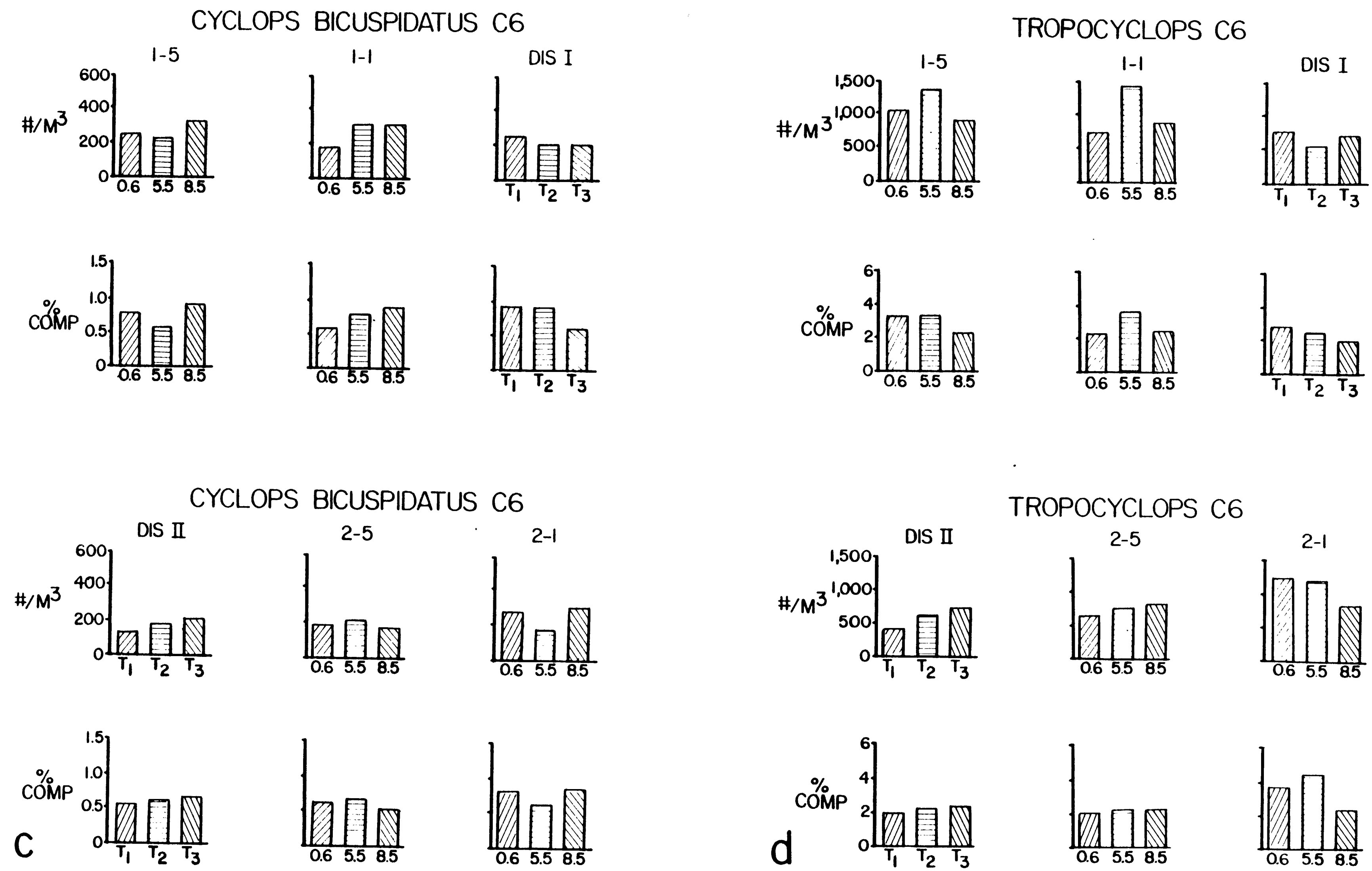

FIG. 53. Continued. c) _Cyclops bicuspidatus thomasi_ C6, d) _Tropocyclops prasinus mexicanus_ C6,

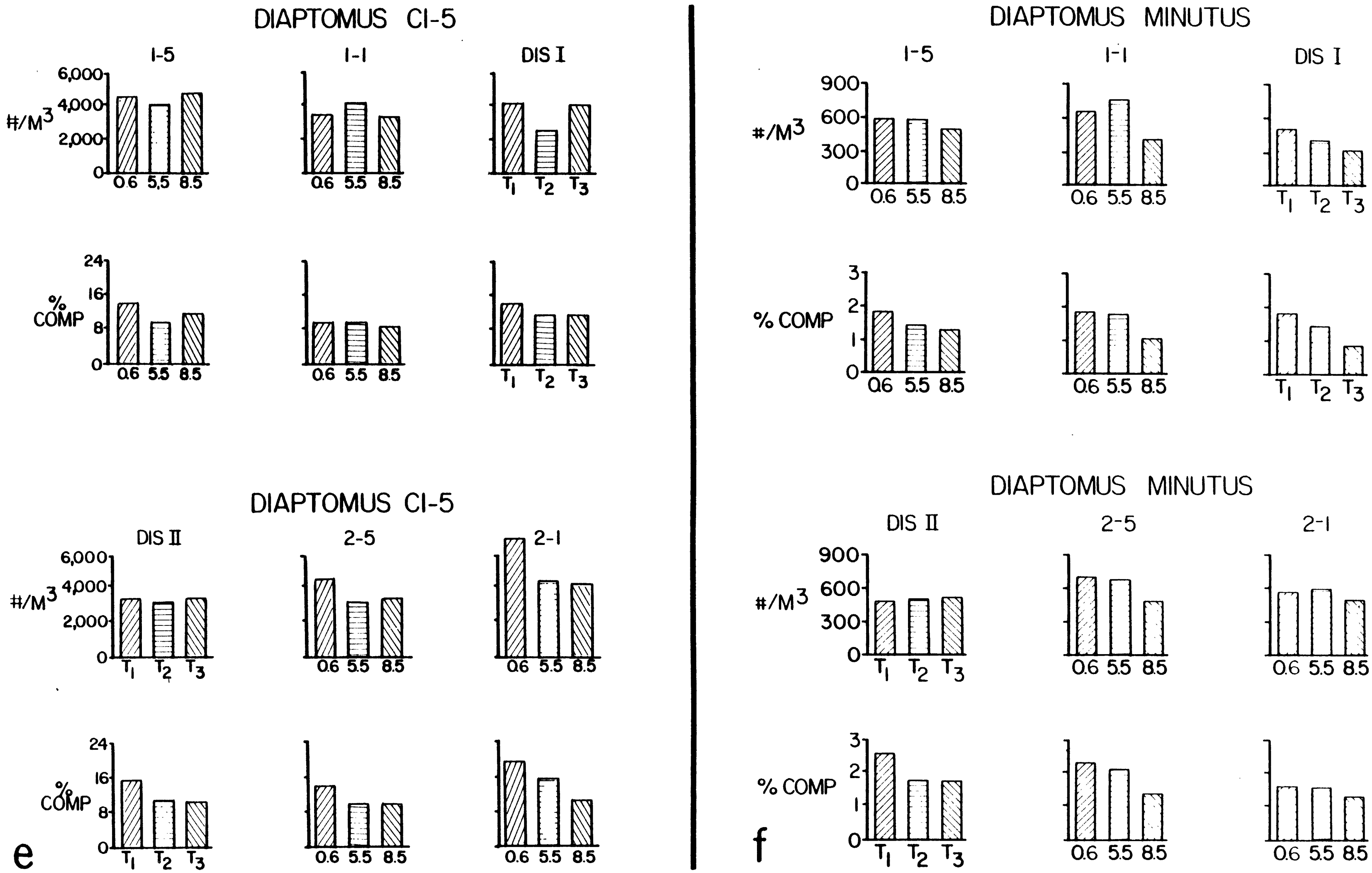

FIG. 53. Continued. e) Diaptomus spp. C1-C5, f) Diaptomus minutus C6,

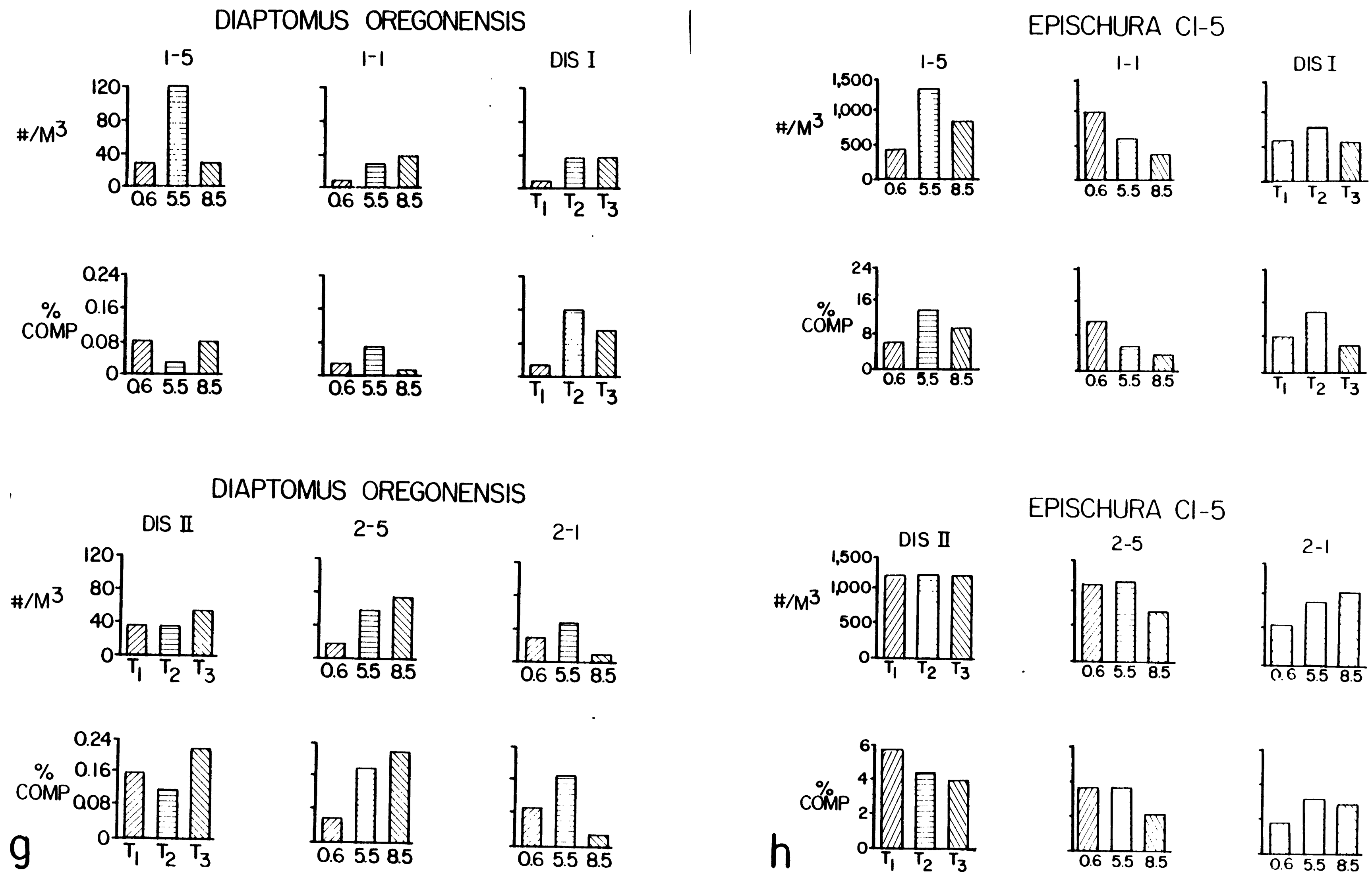

FIG. 53. Continued. g) Diaptomus oregonensis C6, h) Epischura lacustris C1-C5,

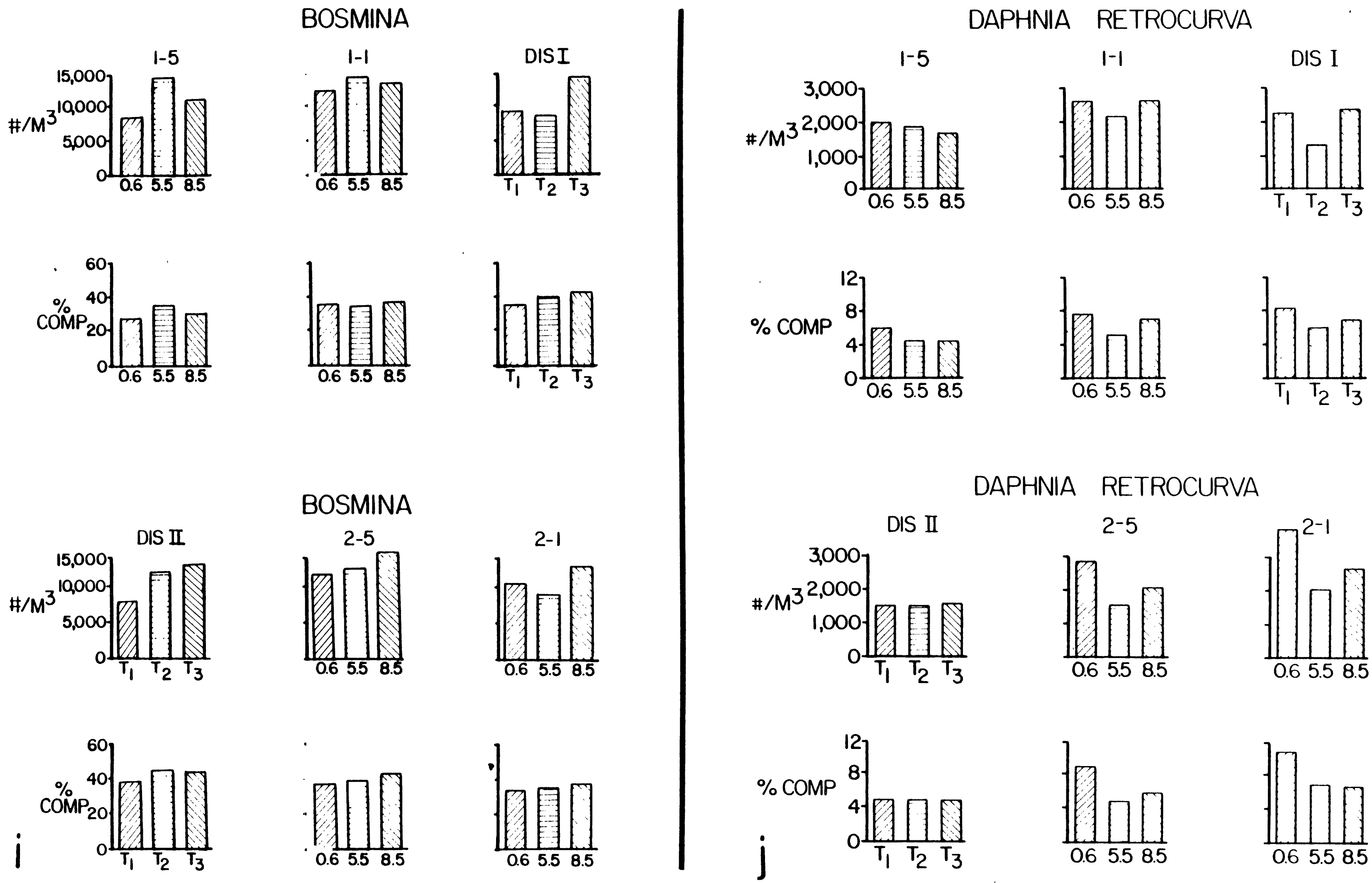

FIG. 53. Continued. i) <u>Bosmina longirostris</u>, j) <u>Daphnia retrocurva</u>,

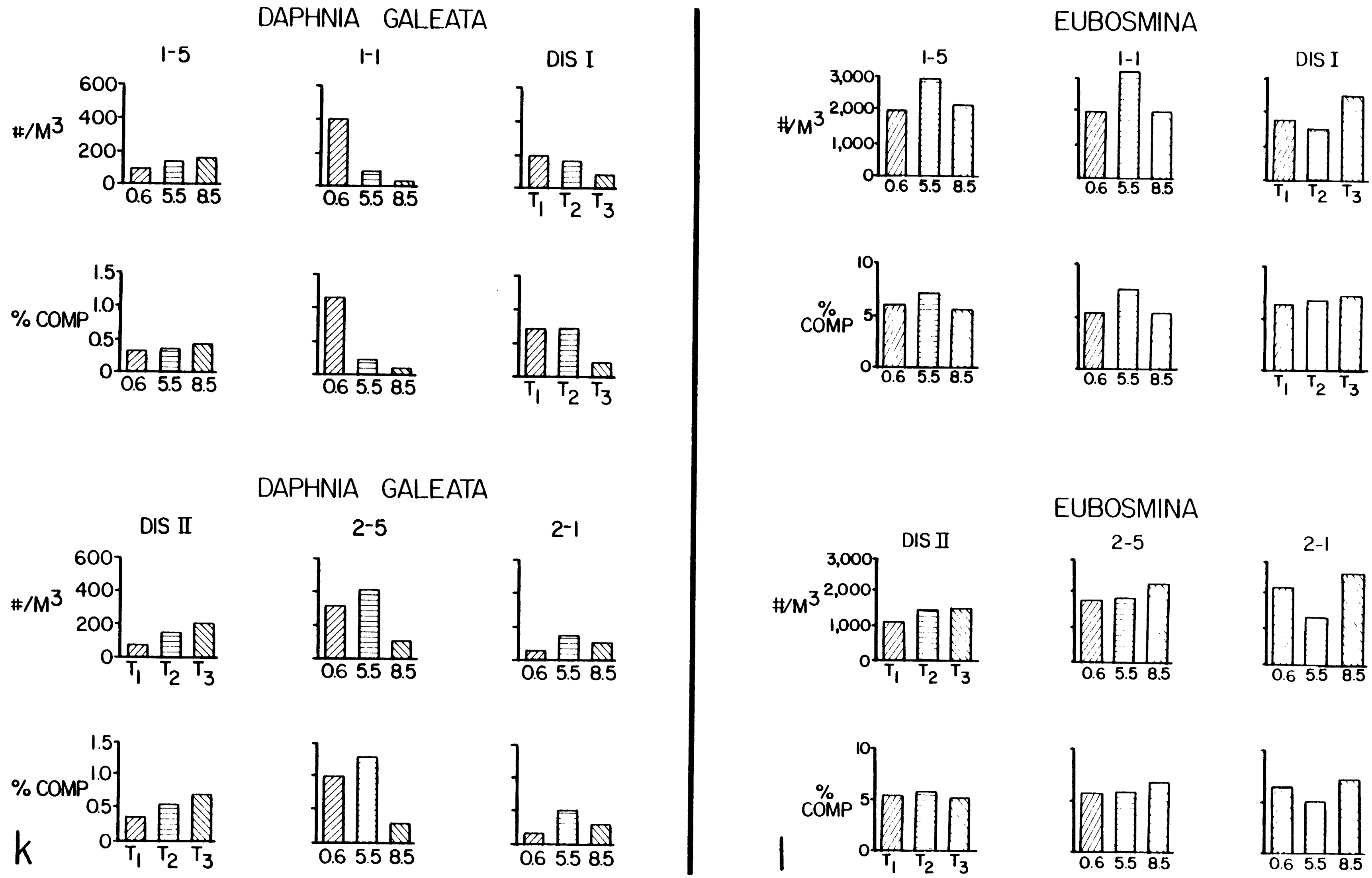

Fig. 53. Continued. k) Daphnia galeata mendotae, l) Eubosmina coregoni,

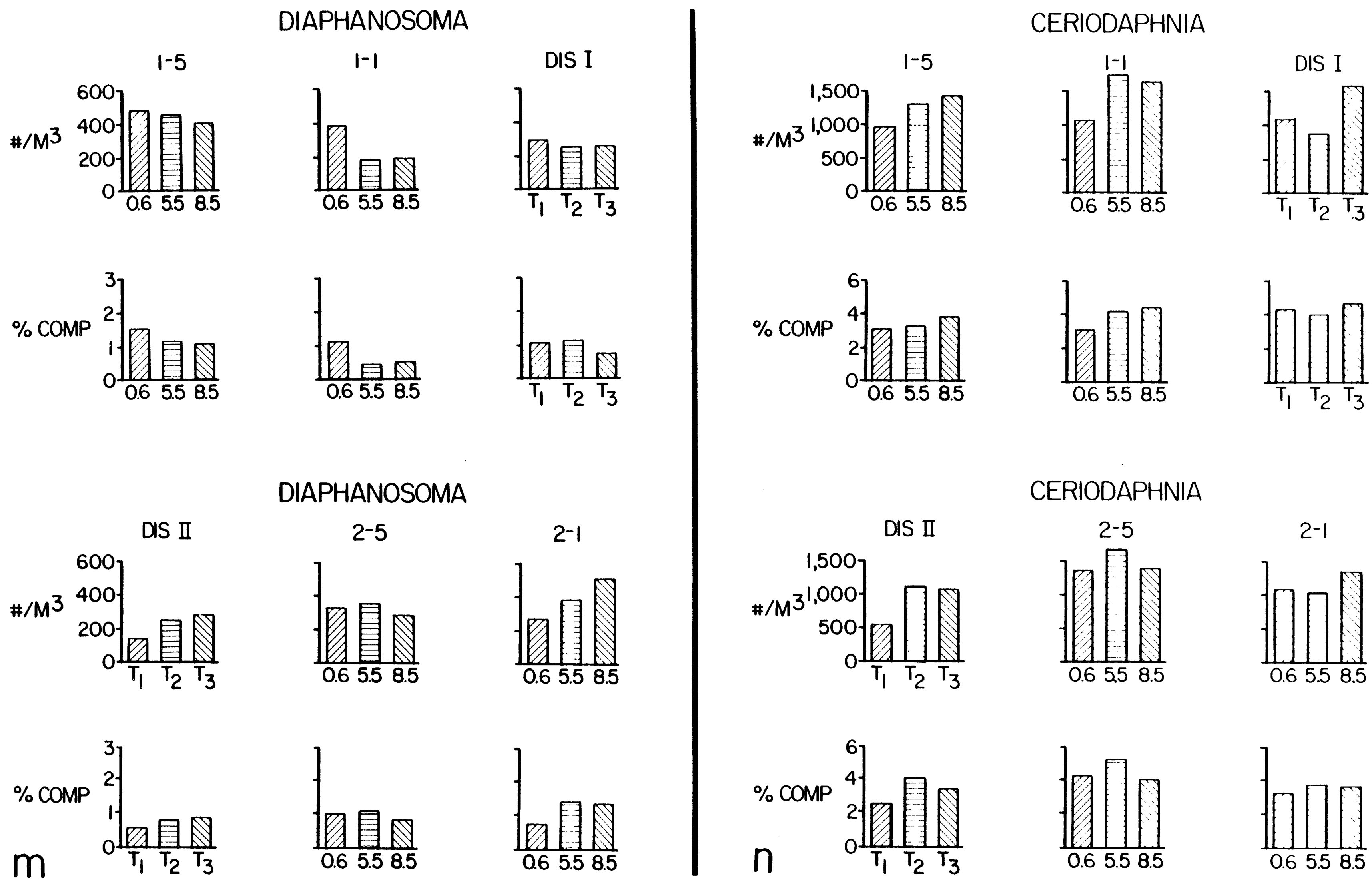

FIG. 53. Concluded. m) Diaphanosoma spp., n) Ceriodaphnia spp.

Table 18. Results of factorial (grate X depth) ANOVA on log transformed intake abundance data for zooplankton taxa examined in the heterogeneity study. A value of ns indicates the effect was not significant at the 95% level.

Taxon	Grate	Source of Variance Depth	G X D
Copepod nauplii	.001	ns	ns
Cyclops spp. C1-C5	.005	.01	ns
Cyclops bicuspidatus thomasi C6	ns	ns	ns
Tropocyclops prasinus mexicanus C1-C6	.05	ns	ns
Diaptomus spp. C1-C5	.025	ns	ns
Diaptomus minutus C6	ns	ns	ns
Diaptomus oregonensis C6	ns	ns	ns
Epischura C1-C5	ns	ns	ns
Bosmina longirostris	ns	ns	ns
Ceriodaphnia spp.	ns	ns	ns
Daphnia galeata mendotae	ns	ns	ns
Daphnia retrocurva	.01	.005	ns
Diaphanosoma spp.	ns	ns	ns
Eubosmina coregoni	ns	ns	ns
Total zooplankton	ns	ns	ns

The only significant time effect was found for adult _Diaptomus minutus_ percentage composition. _D. minutus_ adults formed a larger fraction of the zooplankton at all sampling locations for the 0.6-m depth/time set (Fig. 53). Nauplii, immature _Cyclops spp._ copepodites, and immature _Epischura lacustris_ copepodites had significantly different abundances and compositions between the two discharges. Immature _E. lacustris_ copepodites were more abundant in the Discharge 2 samples while nauplii and immature _Cyclops spp_. copepodites were more abundant in Discharge 1 samples.

Table 19. Results of factorial (grate X depth) ANOVA on inverse-sine square root transformed intake abundance data for zooplankton taxa examined in the heterogeneity study. A value of ns indicates the effect was not significant at the 95% level.

Taxon	Source of Variance		
	Grate	Depth	G X D
Copepod nauplii	.001	ns	ns
Cyclops spp. C1-C5	ns	ns	ns
Cyclops bicuspidatus thomasi C6	ns	ns	ns
Tropocyclops prasinus mexicanus C1-C6	.01	.01	ns
Diaptomus spp. C1-C5	.001	.005	ns
Diaptomus minutus C6	ns	.01	ns
Diaptomus oregonensis C6	ns	ns	ns
Epischura C1-C5	ns	ns	ns
Bosmina longirostris	.01	ns	ns
Ceriodaphnia spp.	ns	ns	ns
Daphnia galeata mendotae	ns	ns	ns
Daphnia retrocurva	.001	.001	ns
Diaphanosoma spp.	ns	ns	ns
Eubosmina coregoni	ns	ns	ns

Results of the *a priori* t-tests for differences in abundance between intake versus discharge samples are presented in Table 22. Significant differences were found between intake and discharge abundances of several taxa in the 0.6-m and 5.5-m depth/time sets and for one taxon in the 8.5-m set. In all of these cases, the intake samples had significantly higher abundances than the discharge samples. For the taxa tested, there were no instances in which the discharge samples had significantly higher abundances than the intake samples.

Table 20. Results of factorial (location X time) ANOVA on log transformed discharge abundance data for zooplankton taxa examined in the heterogeneity study. A value of ns indicates the effect was not significant at the 95% level.

Taxon	Source of Variance Location	Time	L X T
Copepod nauplii	.005	ns	ns
Cyclops spp. C1-C5	.05	ns	ns
Cyclops bicuspidatus thomasi C6	ns	ns	ns
Tropocyclops prasinus mexicanus C1-C6	ns	ns	.025
Diaptomus spp. C1-C5	ns	ns	ns
Diaptomus minutus C6	ns	ns	ns
Diaptomus oregonensis C6	ns	ns	ns
Epischura C1-C5	.025	ns	ns
Bosmina longirostris	ns	ns	ns
Ceriodaphnia spp.	ns	ns	ns
Daphnia galeata mendotae	ns	ns	ns
Daphnia retrocurva	ns	ns	ns
Diaphanosoma spp.	ns	ns	ns
Eubosmina coregoni	ns	ns	ns
Total zooplankton	ns	ns	ns

Results of the one-way analysis of variance for differences in abundance between any of the sampling locations are presented in Table 23. In most cases, the significant differences detected by the _a priori_ t-tests (Table 22) correspond to significant differences between locations detected using the analysis of variance (Table 23). For the cases in which the analysis of variance indicated significant differences in abundance between locations, _a posteriori_ inspection was made for pairwise differences between locations using

Table 21. Results of factorial (location X time) ANOVA on inverse-sine square root transformed discharge percent composition data for zooplankton taxa examined in the heterogeneity study. A value of ns indicates the effect was not significant at the 95% level.

Taxon	Source of Variance		
	Location	Time	L X T
Copepod nauplii	.001	ns	ns
Cyclops spp. C1-C5	.025	ns	ns
Cyclops bicuspidatus thomasi C6	ns	ns	ns
Tropocyclops prasinus mexicanus C1-C6	ns	ns	ns
Diaptomus spp. C1-C5	ns	ns	ns
Diaptomus minutus C6	.01	.025	ns
Diaptomus oregonensis C6	ns	ns	ns
Epischura C1-C5	.01	ns	ns
Bosmina longirostris	ns	ns	ns
Ceriodaphnia spp.	ns	ns	ns
Daphnia galeata mendotae	ns	ns	ns
Daphnia retrocurva	ns	ns	ns
Diaphanosoma spp.	ns	ns	ns
Eubosmina coregoni	.025	ns	ns

Scheffé simultaneous tests (Table 24). Discharge 2 shows significantly ($p<0.10$) lower abundances for several taxa when paired with locations MTR 1-1, MTR 1-5, MTR 2-1, or Discharge 1. Conversely, grates MTR 1-1 and MTR 1-5 had statistically similar abundances which were never found to be significantly lower than any other sampling location in these paired tests.

Table 22. Results of the *a priori* t-tests for differences between intake and discharge samples in each depth/time series for zooplankton taxa examined in the heterogeneity study. ns indicates differences were not significant at the 95% level.

Taxon	Depth/Time Series 0.6 m	5.5 m	8.5 m
Copepod nauplii	.001	.001	.001
Cyclops spp. C1-C5	.005	.002	ns
Cyclops bicuspidatus thomasi C6	ns	ns	ns
Tropocyclops prasinus mexicanus C1-C6	.05	.002	ns
Diaptomus spp. C1-C5	ns	.025	ns
Diaptomus minutus C6	ns	.025	ns
Diaptomus oregonensis C6	ns	ns	ns
Epischura C1-C5	ns	ns	ns
Bosmina longirostris	ns	ns	ns
Ceriodaphnia spp.	ns	ns	ns
Daphnia galeata mendotae	ns	ns	ns
Daphnia retrocurva	.02	ns	ns
Diaphanosoma spp.	ns	ns	ns
Eubosmina coregoni	.03	ns	ns
Total zooplankton	.002	.01	ns

Representative Intake Forebay Sampling Locations

A procedure derived from formulae given by Kirk (1968, pp. 74-76) was used to evaluate how representative were samples obtained from the four intake locations and three depths. This is the same procedure as previously used to examine heterogeneity of zooplankton abundance within the forebay (Evans 1975). First, the mean abundance of zooplankton in the intake forebay ($\overline{x}_F$) was calculated and compared to the mean abundances at each of the 12 grate-depth

Table 23. Results of one-way ANOVA for differences in log transformed abundance data between all sampling locations (intake grates and discharge locations) in each depth/time series for zooplankton taxa examined in the heterogeneity study. ns indicates differences were not significant at the 95% level.

Taxon	Depth/Time Series 0.6 m	5.5 m	8.5 m
Copepod nauplii	.001	.001	.006
Cyclops spp. C1-C5	.005	.01	ns
Cyclops bicuspidatus thomasi C6	ns	ns	ns
Tropocyclops prasinus mexicanus C1-C6	ns	.01	ns
Diaptomus spp. C1-C5	ns	ns	ns
Diaptomus minutus C6	ns	ns	ns
Diaptomus oregonensis C6	ns	ns	ns
Epischura C1-C5	.04	ns	ns
Bosmina longirostris	ns	.04	ns
Ceriodaphnia spp.	ns	ns	ns
Daphnia galeata mendotae	ns	ns	ns
Daphnia retrocurva	.04	ns	ns
Diaphanosoma spp.	ns	ns	ns
Eubosmina coregoni	ns	ns	ns
Total zooplankton	.02	.04	ns

sampling locations ($\bar{x}_{g,d}$). Differences ($d_{g,d}$) between grate-depth location means and the forebay mean are expressed in Table 25 both in abundance units and as a percentage of the forebay mean. Second, the 95% confidence limits for these differences were calculated from the equation:

$$d_{g,d} \pm t_{.05[\nu]} \sqrt{\frac{MS(p-1)}{pm}}$$

Table 24. Results of *a posteriori* Scheffé simultaneous tests for pairwise differences in log transformed abundances between sampling locations (intake grates and discharge locations) in depth/time series for selected zooplankton taxa. A value of ns indicates the Scheffé contrast was not significant at the 90% level. For all significant ($p < .10$) differences shown, the first sampling location had higher abundance than the second in the pair.

Location Comparison	Total (0.6 m)	Total (5.5 m)	Nauplii (0.6 m)	Nauplii (5.5 m)	Nauplii (8.5 m)	*Tropocyclops* (5.5 m)	*Cyclops* C1-C5 (0.6 m)	*Cyclops* C1-C5 (5.5 m)	*Epischura* (0.6 m)	*Bosmina* (5.5 m)	*Daphnia retrocurva* (0.6 m)
MTR 1-1 vs.											
MTR 1-5	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
MTR 2-1	ns	ns	ns	.05	ns	ns	ns	ns	ns	ns	ns
MTR 2-5	ns	ns	.05	ns	ns	ns	ns	ns	ns	ns	ns
Discharge #1	ns	.10	ns	.05	.10	.05	ns	ns	ns	ns	ns
Discharge #2	.05	ns	.01	.01	.05	.10	.05	.05	ns	ns	ns
MTR 1-5 vs.											
MTR 2-1	ns	ns	.10	.05	ns	ns	ns	ns	ns	ns	ns
MTR 2-5	ns	ns	.05	ns	ns	ns	ns	ns	ns	ns	ns
Discharge #1	ns	.10	.10	.05	.10	.10	ns	ns	ns	ns	ns
Discharge #2	.10	ns	.01	.01	.05	ns	.01	.05	ns	ns	ns
MTR 2-1 vs.											
MTR 2-5	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Discharge #1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Discharge #2	.05	ns	ns	ns	ns	ns	.10	ns	ns	ns	.10
MTR 2-5 vs.											
Discharge #1	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Discharge #2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Discharge #1 vs.											
Discharge #2	ns	ns	.10	ns	ns	ns	.05	ns	ns	ns	ns

Table 25. Difference ($d_{g,d}$) between location mean ($\bar{x}_{g,d}$) and forebay mean ($\bar{x}_F$), both in abundance units (animals/m^3) and as a percentage of the forebay mean, for the heterogeneity study. * indicates differences that were significantly ($p<0.05$) different from zero.

Location	Depth 0.6 m	Depth 5.5 m	Depth 8.5 m
MTR1-1		*	
#/m^3	-447	+6486	+2182
%	-1.3%	+18.5%	+6.2%
MTR 1-5			
#/m^3	-3233	+5279	+2802
%	-9.2%	+15.1%	+8.0%
MTR 2-1		*	
#/m^3	-994	-6944	+1752
%	-2.8%	-20.0%	+5.0%
MTR 2-5			
#/m^3	-3545	-2993	-340
%	-10.1%	-8.5%	-1.0%

where $d_{g,d} = \bar{x}_{g,d} - \bar{x}_F$

MS = within cell variance (error mean square)

p = number of levels (12)

m = number of observations at each level (2)

ν = degrees of freedom within cells (12)

t = Student's t

If the interval defined by the upper and lower confidence limits for a $d_{g,d}$ contains the value zero, then the location mean is not significantly different ($p < 0.05$) from the forebay mean. If the interval does not include zero, then the location mean is significantly different from the forebay mean. The 95%

confidence limits for $d_{MTR1-5,5.5m}$ are defined by +15.1% $\pm$ 16.6%. As this interval includes zero, the mean abundance at this location is not significantly different ($p < 0.05$) from the forebay mean and MTR 1-5, 5.5 m can be considered a representative sampling location for the forebay. Only two location means, those of MTR 1-1, 5.5 m and MTR 2-1, 5.5 m, were significantly different from the forebay mean (Table 25).

Comparisons of Intake and Discharge Abundance Estimates over the 1975-1978 Period

The present and previous (Evans 1975) heterogeneity analyses have indicated some differences in density estimates of zooplankton between intake and discharge waters. In addition to the patchiness of zooplankton within the forebays examined in the heterogeneity studies, it is appropriate to investigate whether there are longer term trends for either intake or discharge density estimates to be consistently higher. Clearly, the number of zooplankton entering the plant in the cooling water must equal the number that exit the plant in that water mass: no net gains or losses of zooplankton (live plus dead) can be readily conceived during the 2-minute passage time. A consistent discrepancy between intake and discharge zooplankton densities between intake and discharge may indicate that a consistently heterogeneous environment is maintained within the forebays, and that our fixed sampling locations reflect these heterogeneities.

Results of applying the median test to examine differences between total zooplankton densities of paired intake and discharge station means are shown in Table 26. All available entrainment abundance data, including the weekly sampling, were included in these analyses. For 21 pairs of density values

Table 26. Results of the median test for differences in abundance estimates between intake and discharge sampling locations.

		Signif.
Comparisons for the 1975-1978 period.		
Discharge #1 < Discharge #2	13 of 21 dates	ns
Discharge #1 < MTR1-5	126 of 199 dates	$p < 0.01$
MTR1-5 < Discharge #2	19 of 39 dates	ns
Comparisons for Discharge #1 and MTR1-5 by year.		
1975 Discharge #1 < MTR1-5	23 of 35 dates	ns
1976 Discharge #1 < MTR1-5	48 of 59 dates	$p < .001$
1977 MTR1-5 < Discharge #1	33 of 59 dates	ns
1978 Discharge #1 < MTR1-5	29 of 46 dates	ns

obtained from Unit 1 and Unit 2 discharges, 13 of these pairs had higher Discharge 2 densities than Discharge 1. The median test indicates that this is not a statistically significant trend ($p < 0.05$, Table 26). Likewise, zooplankton density estimates for Discharge 2 did not exhibit a statistically significant trend of being higher than paired density estimates from Intake MTR 1-5. However, 63.3% of the pairs of density estimates for Intake MTR 1-5 and Discharge 1 had higher mean density estimates for the intake waters. This is a statistically significant ($p<0.05$, Table 26) trend over the 1975-1978 period. An examination of Intake MTR 1-5 versus Discharge 1 densities for individual years reveals that intake densities tended to be higher than

Discharge 1 densities three of four years but that this trend was significant only during 1976 (Table 26).

DISCUSSION

In the 1975 to 1976 operational period, Evans et al. (1978) stated that it was unlikely that losses of zooplankton due to plant passage had an adverse impact on water or sediment quality in the nearshore area. Although the maximum loss of zooplankton due to condenser passage was estimated as averaging 412 kg dry wt/month, these dead zooplankton were dispersed over a wide area (more than 2.2 km^2) as they settled out of the water column. Depositional rates were estimated at 6.2 $mg/m^2/day$ in comparison to an estimated natural deposition rate of 2,800 $mg/m^2/day$, i.e., 0.2% of the estimated natural rate. This additional deposition of detrital zooplankton was unlikely to affect water and sediment quality adversely in the vicinity of the plant, particularly as the nearshore region is not an area of net deposition. Rather, currents transport much of the material to depositional basins.

Entrainment studies conducted in 1977 and 1978 continue to suggest that detrital zooplankton do not adversely affect the nearshore region in the vicinity of the plant. The estimated maximum loss due to plant passage, 1,232 kg/month, still is comparatively low and adds little to the natural deposition which occurs in the area. Furthermore, preliminary results of a study conducted of the epibenthic and benthic community in the vicinity of the plant in July 1980 suggest that the plant does not adversely affect populations in the discharge area.

The entrainment program provides detailed information on variability in zooplankton abundances at shorter time intervals than does the lake survey

program. These data reveal fairly large variability from week to week, indicating that a single cruise conducted in a month does not provide a precise population estimate for that month. Thus, some caution must be employed in interpreting differences between individual cruises conducted in successive years. Trends may exist in the data (Section 2), but these may not be consistent from year to year because of slight differences in seasonality. A good example of this is Damann's 1960 study which shows a trend of increasing phytoplankton populations in the vicinity of the intakes at Chicago for the 1926 to 1958 period: while trends were apparent, there were some years in the later part of his study in which phytoplankton concentrations were as low as in the late 1920s.

Entrainment sampling provides an opportunity to obtain more precise estimates of zooplankton population characteristics without the high costs entailed with ship operation. Furthermore, it is possible to collect entrainment samples at most times (the exception being when the plant does not circulate water), whereas cruises are limited by weather and season. Analysis of the entrainment and nearshore (within the 10-m depth contour) data indicates that the plant does provide a good estimate of lake populations. While there are some differences between zooplankton abundances in the cooling waters and the lake, these can be adjusted for by use of an appropriate regression equation for the numerically abundant zooplankton. While such regressions cannot be developed for the rare epibenthic zooplankton, such taxa are of secondary interest in analyzing data for long-term increases in the abundance of total zooplankton and shifts in the abundance of dominants. Thus studies at the Donald C. Cook Plant provide an opportunity to investigate long-term changes in zooplankton populations in southeastern Lake Michigan and potentially could

prove as valuable as similar studies of phytoplankton conducted at various intakes. High flow rates into the plant and the use of a high capacity sampling pump allow good estimates of nearshore lake populations with minimal concerns of pump avoidance and other sampling biases.

SECTION 5

STATISTICAL COMPARISONS OF ZOOPLANKTON POPULATIONS WITHIN AND ADJACENT TO THE THERMAL PLUME DURING AN UPWELLING

INTRODUCTION

Evans et al. (1978) presented results of a study conducted in September 1976 of zooplankton populations within and adjacent to the thermal plume. Samples were collected from 1-m depths along a series of 12 transects extending approximately 1,800 m north and south of the plant site and 1,600 m offshore. Elevated zooplankton concentrations were observed in the immediate vicinity of the plume and it was hypothesized that vertical displacement was the primary factor producing observed patterns.

This study was repeated in June 1977. There were two major objectives to this second study. The first was to determine how representative were the results of the September 1976 study. The second was to test the hypothesis that the elevated zooplankton abundance observed in the vicinity of the discharge jets was due to vertical displacement of deeper-living zooplankton.

MATERIALS AND METHODS

Two series of transects were run on June 15, 1977. The first was conducted between 11:21 and 15:06 EDT along 12 transects extending 1,800 m north and south of the discharge jets and 1,600 m offshore. One hundred and nine samples were collected at a sampling depth of 1 m during this series. In the second transect series 87 samples were collected from a depth of 3 m between 15:37 and 18:31 EDT.

A centrifugal pump and hose system was used to collect zooplankton. Water passed from the 5.0-cm diameter hose, through the pump, and then was discharged through a 7.6-cm diameter hose and PVC pipe into a 0.2-m^3 barrel of water. A 30-cm diameter, 156-μ mesh net was suspended in the barrel to reduce structural damage to zooplankton during filtration. The intake hose was equipped with a checkvalve (to aid in pump priming), a series of fairings, and a vane (to reduce turbulence during towing). A 23-kg cable depressor helped to maintain a low wire angle during sample collection.

Samples were collected for exactly 2 minutes (timed with a stopwatch) while the pump was in continuous operation as the ship travelled along the transects. Ship speed was approximately 3.5 knots so that each 2-minute sample was collected over an approximate distance of 200 m. Approximately 0.8 m^3 of water was filtered during each sampling period.

Two thermistors were connected to chart recorders to provide continuous temperature measurements. One thermistor, from a YSI model-54 oxygen meter, was suspended several centimeters below the water surface in the ship's wake. Temperature data from this thermistor are assumed to be representative of temperatures at a depth of approximately 0.5 m. The second thermistor was placed in the discharge pipe of the pumping apparatus. An error in setting up the chart recorder for this thermistor was not detected until most of the 1-m transect was completed. Thus, two simultaneous temperature measurements for water from two depths were available for the 3-m transect series and for water from similar depths for part of the 1-m transect series.

A Motorola Mini-Ranger II was installed on shipboard and two transponders placed on shore. Readings from the Mini-Ranger were taken every minute to give

ship location within meters. Winds were 5 to 10 knots from the north and seas were less than 24 cm. The air temperature was 21-22° C.

In addition to the transect series, three additional stations were examined to determine zooplankton distribution with depth. The first station was located at the inshore leg of the northernmost transect; zooplankton samples were collected between 11:10-11:17 EDT from depths of 1, 2, 3, and 4 m. The second station was located at the inshore end of the southernmost transect and was sampled between 15:07-15:22 EDT at sampling depths of 1, 2, 3, and 4 m. The last station, sampled between 18:44-19:05 EDT at depths of 1, 2, 3, 4, 5, 6, and 7 m, was located east of the intake structures.

While samples were being collected on the lake, an entrainment sample series was collected inside the power plant from the intake forebay (grate MTR1-5, 5.5 m). Methods are as described in Section 4. Single 5-minute samples were collected at 10- to 15-minute intervals between 10:00 and 18:25 EDT to provide a total of 29 samples.

In the laboratory, samples were examined according to the techniques described in Section 1. Approximately every second sample from each of the transect series was examined. Zooplankton from a total of 94 samples were counted and identified. These data provided detailed information on zooplankton distributions within and adjacent to the thermal plume: the additional time required to work up the remaining samples would not have provided significantly new information. All the pump profile samples were examined, and eight of the entrainment samples were examined. Because zooplankton entrainment abundances remained remarkably consistent over the sampling period, the remaining samples in the entrainment series were not examined.

Patterns of zooplankton density were examined with principal component analysis. The analysis was based on the variance-covariance matrix of the log-transformed (numbers/m^3 + 1) data. Thirteen categories of copepods, cladocerans, and rotifers were used in the analysis. Analyses were performed with the 1-m data, the 3-m data, and the combined 1- and 3-m data. Here we report the results of the combined data. Correlations between log-transformed taxa densities and the first and second principal components were calculated to assist with the interpretation of the principal components.

RESULTS

While a well-defined thermal plume was observed during the September 1976 study, the plumes observed during the June 1977 study were weak and indistinct (Fig. 54). Patches of warm and cool water were observed during the two 0.5-m mappings (mapped with the same instrument) and the 3-m mapping. Each thermal plume was small with a northwesterly or west-northwesterly direction of flow. Plant operating characteristics were similar to those during the September 1976 study, with approximately 0.57 x 10^6 gallons of water drawn each minute through the plant and heated 9C° before its return to the lake at a discharge temperature of 24°C.

There is evidence that an upwelling occurred during the course of our study. On 14 June, surface temperatures decreased from 15.4°C (day) to 14.2°C (night) at the fish beach stations A and B located a few hundred meters north and south of the plant. On 15 June, the day of our study, fish personnel (D. J. Jude, The University of Michigan, personal communication) measured surface water temperatures of 16°C at station R (a few hundred meters south of the discharge

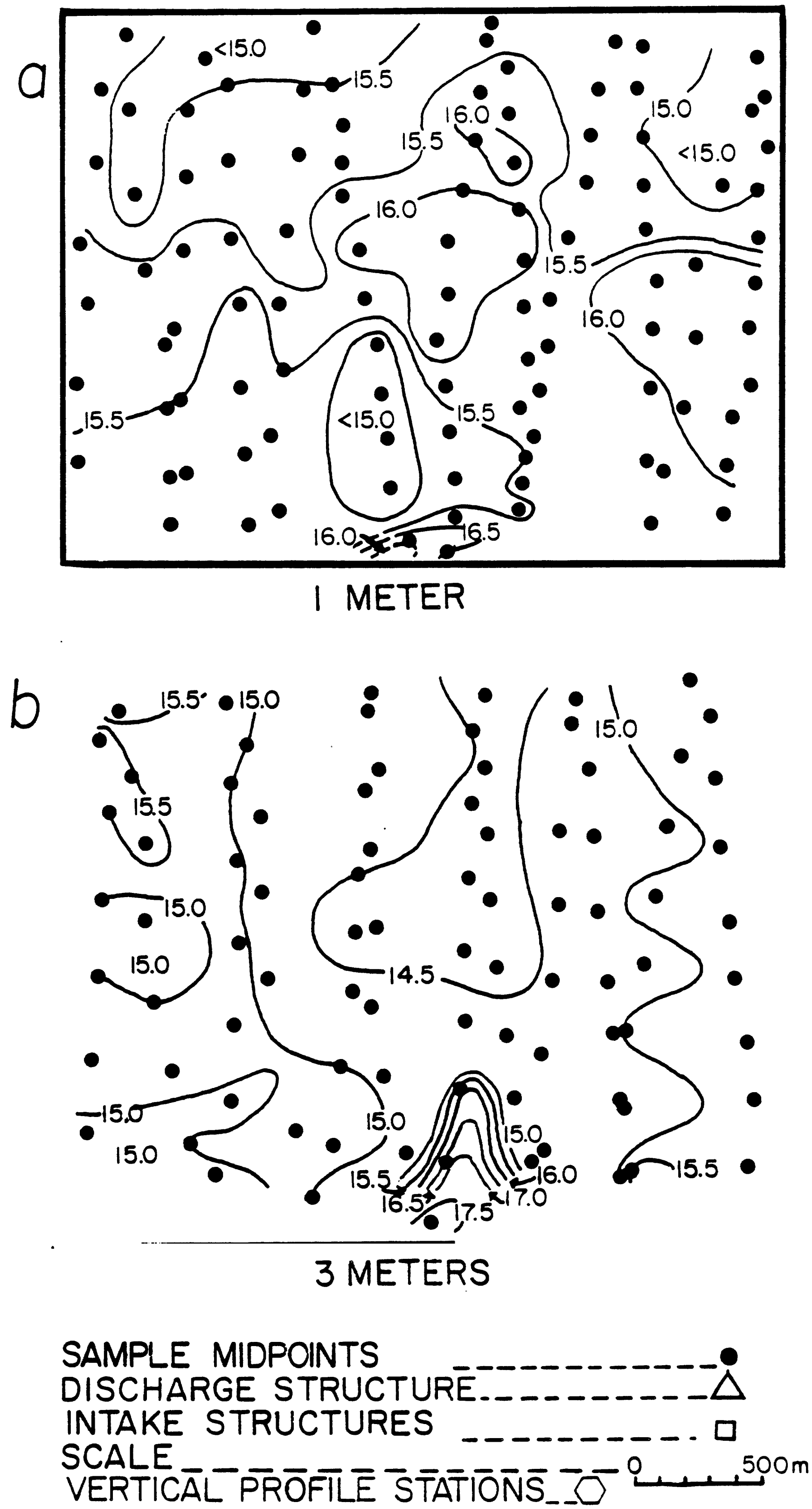

FIG. 54. Water temperature along a) the 1-m transect and b) the 3-m transect on 15 June 1977.

jets). These data are similar to the temperature data we collected during our study. On 16 June, the upwelling was more completely mapped during the short survey cruise (Fig. 2e, Section 1).

One-meter zooplankton distributions in the immediate vicinity of the plume on 15 June were similar to those observed in the September study. High concentrations (>50,000/m^3) were observed near the discharge jets and the region of elevated concentrations had a northwesterly orientation (Fig. 55). June zooplankton abundances at 1-m depths were low (<100/m^3) over the outer half of the transect area but increased shoreward to over 10,000/m^3. This inshore-offshore difference in zooplankton abundance was not observed during the September 1976 study.

Zooplankton abundances at 3-m depths were high, ranging from less than 10,000/m^3 in the southwest region of the transect area to over 50,000/m^3 a few hundred meters offshore of the discharge jets. A patch of water northwest of the intake structures contained more than 100,000/m^3 of zooplankton. Lower abundances (<25,000/m^3) were observed in the vicinity of the discharge structures.

The numerically dominant taxa were immature and adult *Cyclops* spp. copepodites, immature *Diaptomus* spp. copepodites, *Bosmina longirostris*, and *Asplanchna* spp. These taxa occurred in relatively low abundances (Fig. 55) at 1-m depths with abundances increasing toward shore. Maximum 1-m abundances were observed in the vicinity of the discharge jets. At 3-m depths, *Bosmina longirostris*, immature *Cyclops* spp., immature *Diaptomus* spp., and adult *Cyclops* spp. abundances were relatively high both in the cooler waters (<15°C) of the central region of the transect area as well as in the vicinity of the intake

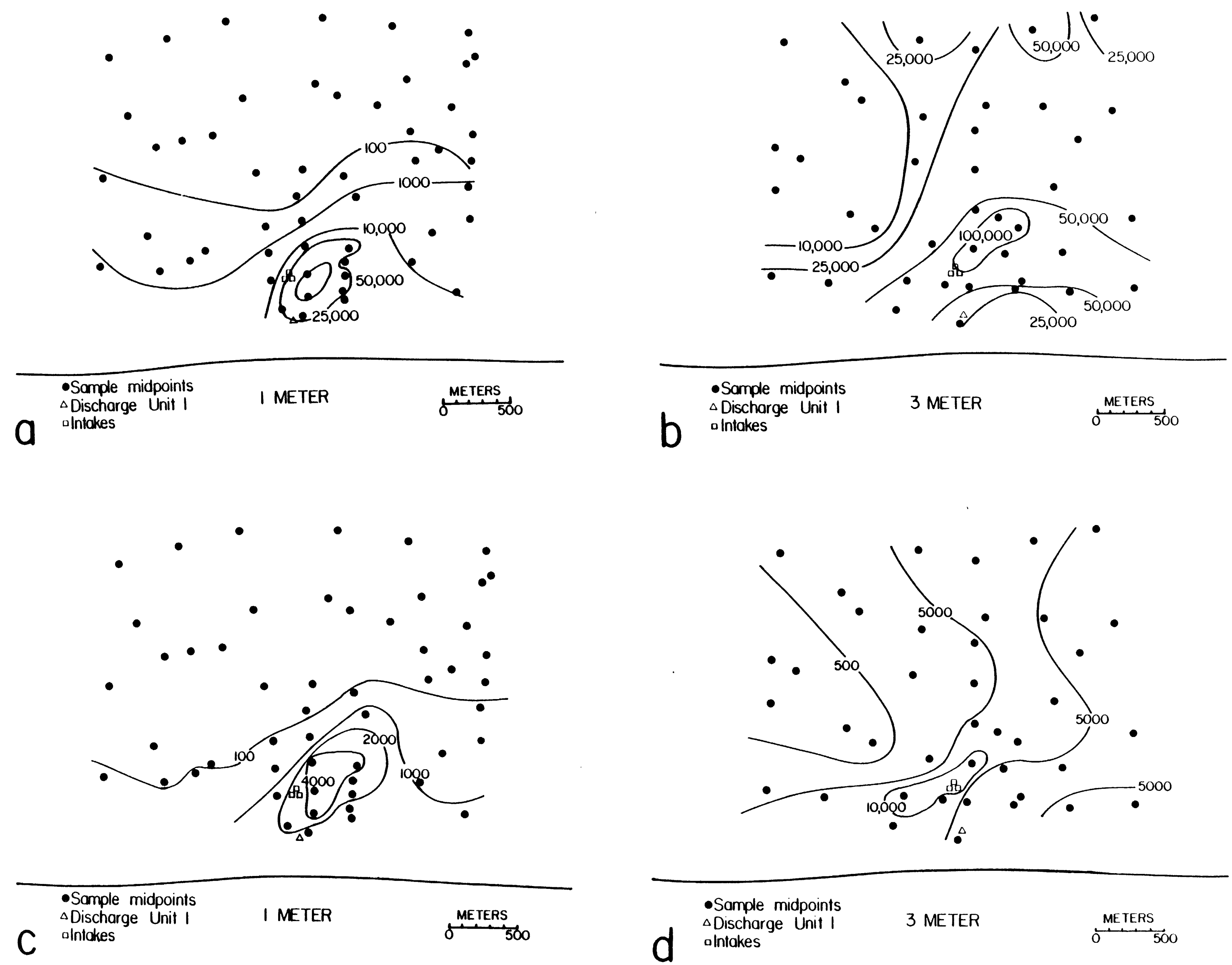

FIG. 55. The distribution of selected zooplankton taxa on 15 June 1977 at the 1-m stratum (left column) and the 3-m stratum (right column). a), b) Total zooplankton; c), d) Cyclops spp. C1-C6;

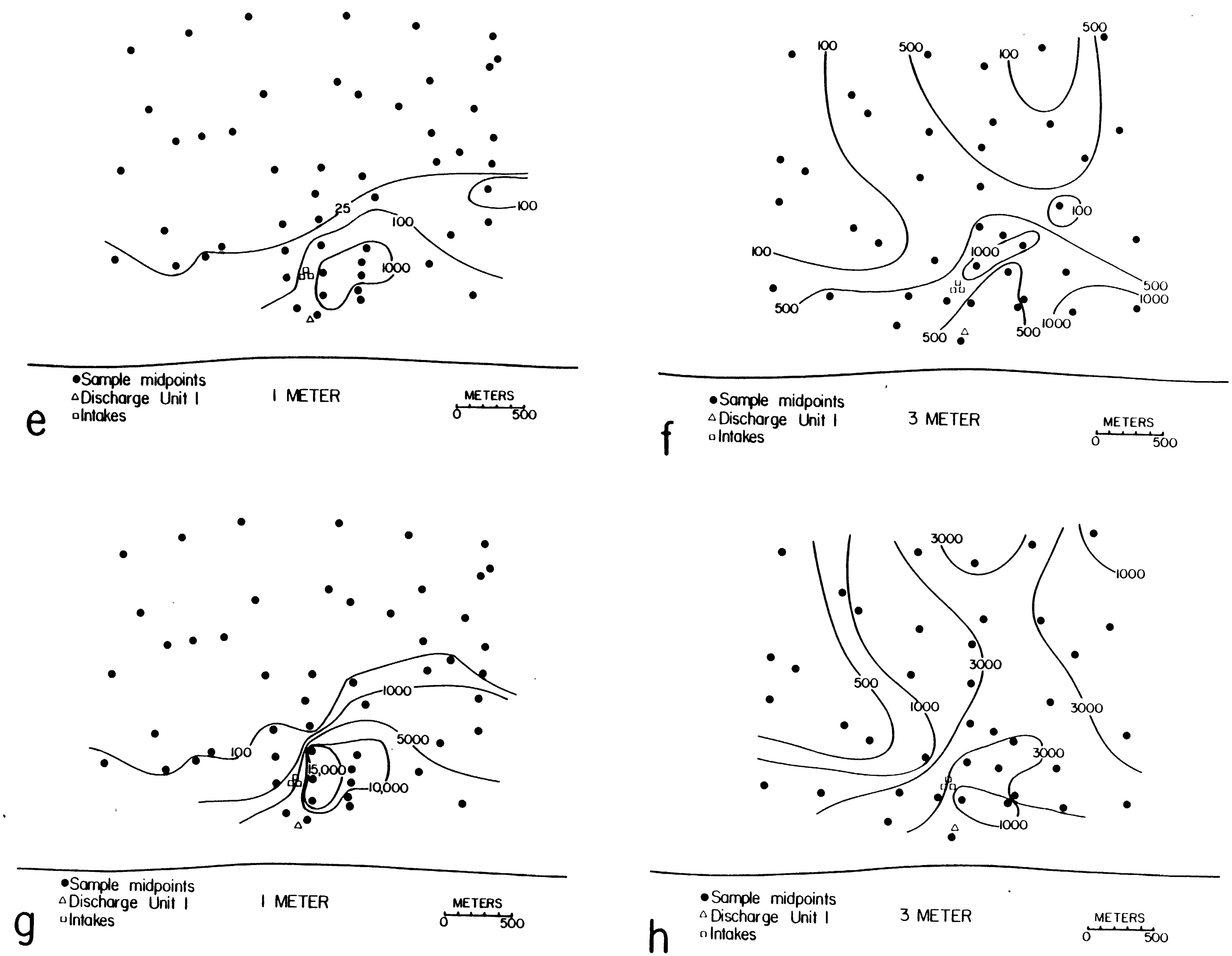

FIG. 55. Continued. e), f) Cyclops spp. C6; g), h) Diaptomus spp. C1-C5;

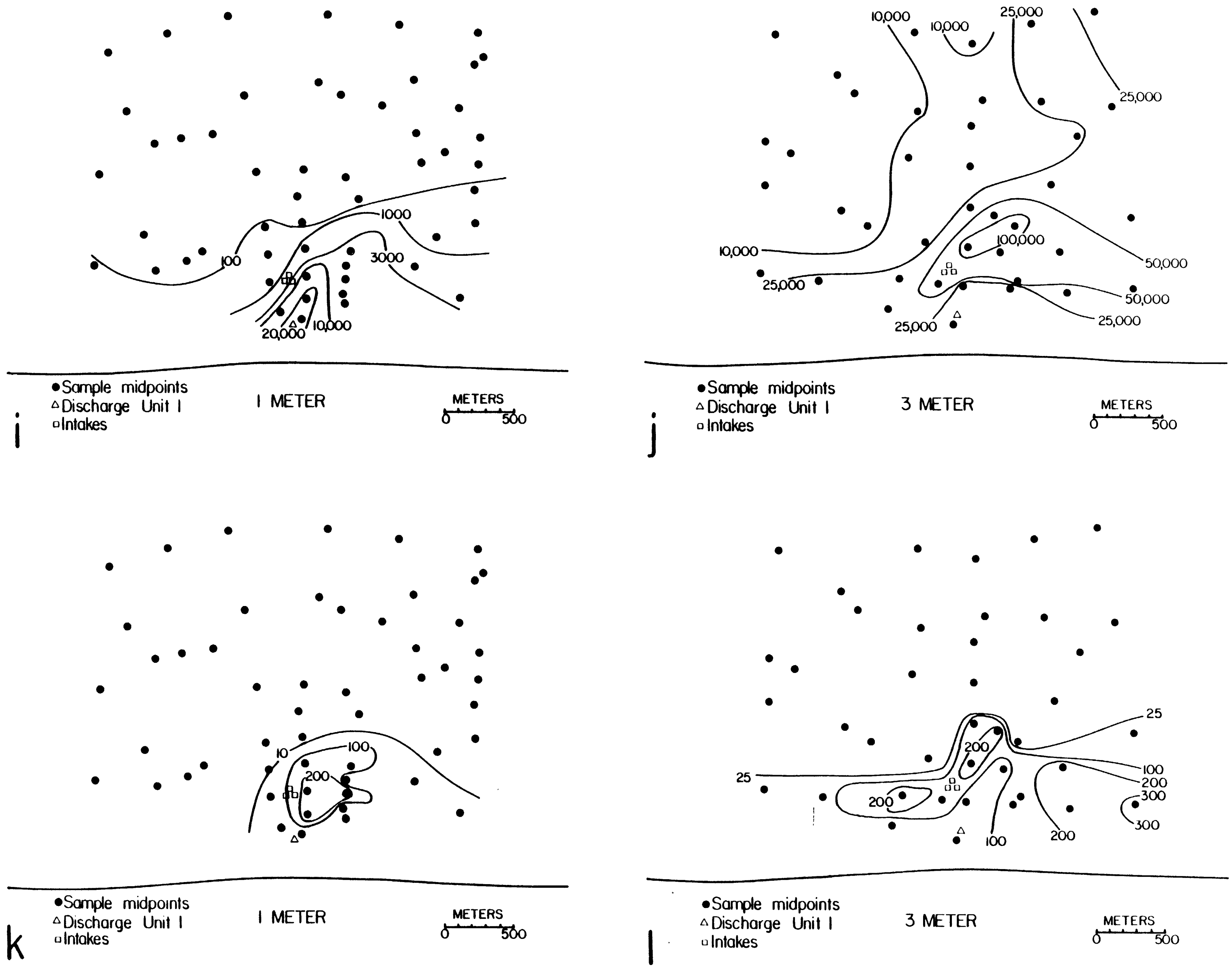

FIG. 55. Continued. i), j) Bosmina longirostris; k), l) Daphnia spp.;

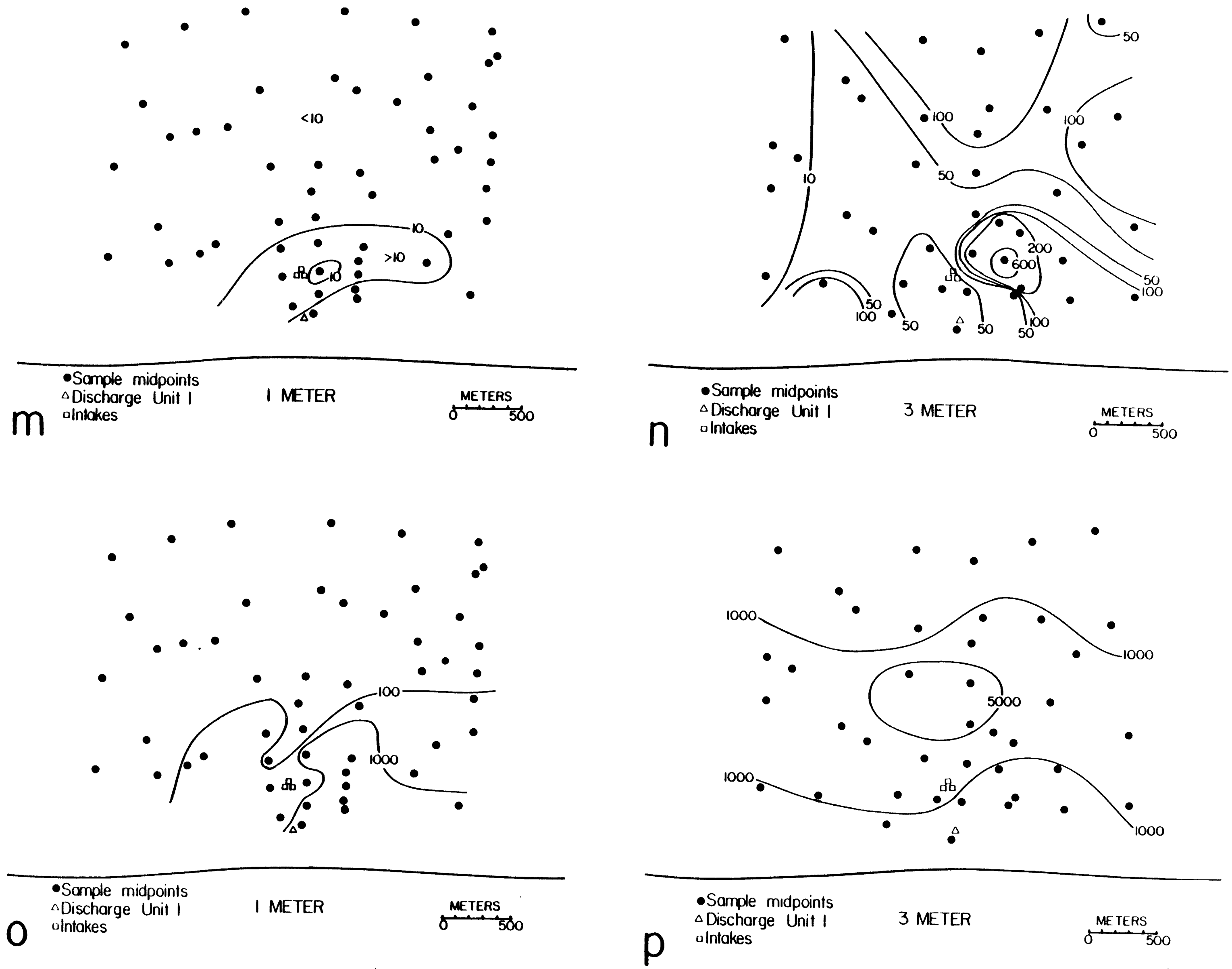

FIG. 55. Concluded. m), n) Eubosmina coregoni; o), p) Asplanchna spp.

structures. Relatively low 3-m depth abundances were observed in the vicinity of the discharge structures. Maximum concentrations of Asplanchna spp. were observed in a band of water running parallel to and a few hundred meters from shore. Taxa abundances were several times greater at 3 m than at 1 m.

The first principle component (PC1) from principal component analyses of the combined 1- and 3-m depth data accounted for 78% of the variance. Taxa correlations (Table 27) with PC1 generally were high. The second principal component (PC2) accounted for only an additional 8% of the variance, and taxa correlations were low.

Plotting stations by their PC1 and PC2 values produced a fan-shaped distribution of stations. The group forming the base of the fan had low PC1 values and extended over approximately 2 PC1 units. The remainder of the PC1 axis was subdivided into four similar-sized PC1 groups. Stations could not be grouped in any meaningful way on the basis of PC2. As PC2 accounted for only 8% of the variance, this was not unexpected.

The resulting five groups were located on the transect area (Fig. 56). Groups 1, 2, and 3 were composed solely of 1-m stations. Group 1 consisted of stations in the outer half of the transect area which had low PC1 values and little variation in PC2 values. With the exception of Group 5, Group 1 was the largest grouping of stations and had relatively uniform zooplankton assemblages. Zooplankton concentrations at these stations were low (Table 27). Group 2, with higher PC1 values, consisted of a narrow band of stations (approximatey 100 m wide) inshore of Group 1. Group 3 extended from Group 2 toward shore except in the vicinity of the plume where it was deflected. Zooplankton concentrations were greater in Group 3 than in Group 2 (Table 27).

Table 27. Linear correlation coefficients (r) between temperature, and principal components 1 and 2, for the transformed ($\log_{10}(x + 1)$) densities of 13 zooplankton taxa and mean taxa abundance (No./m^3) by region (June 15, 1977). Region locations shown in Fig. 5.

Taxon	Correlation (r)			Region (depth)						
	PC 1	PC 2	Temp	1(1 m)	2(1 m)	3(1 m)	4(1 m)	4(3 m)	5(1 m)	5(3 m)
Bosmina longirostris	0.9697	-0.1029	-0.1908	7	38	157	3,281	10,802	15,344	38,719
Diaptomus spp. C1-C5	0.9602	-0.0875	-0.1625	3	86	395	1,991	1,154	3,732	2,922
Cyclops spp. C1-C6	0.9482	-0.1559	-0.0483	13	334	1,206	7,753	2,439	15,445	6,722
Diaptomus ashlandi C6	0.9403	-0.1667	-0.2111	<1	2	18	118	48	325	261
Nauplii	0.9335	0.0095	-0.1617	<1	2	10	85	114	293	137
Asplanchna spp.	0.9245	0.1091	-0.1025	7	71	169	1,314	1,058	1,710	1,792
Diaptomus minutus C6	0.8563	0.3783	-0.2357	2	44	105	280	517	366	956
Eubosmina coregoni	0.8225	-0.0803	-0.2096	<1	3	3	11	40	56	160
Diaptomus oregonensis C6	0.8186	0.0341	-0.2305	<1	5	19	33	28	93	114
Eurytemora affinis	0.7808	0.3821	-0.2750	1	3	4	20	66	63	124
Epischura lacustris C1-C6	0.6984	0.5382	-0.2972	<1	3	9	33	61	19	108
Daphnia spp.	0.6318	-0.6398	0.0697	1	1	5	51	37	228	77
Polyphemus pediculus	0.4692	0.5557	-0.3205	17	16	51	67	101	22	130
Temperature	-0.1894	-0.2790	--							
Total				54	608	2,151	15,037	16,465	37,696	52,222

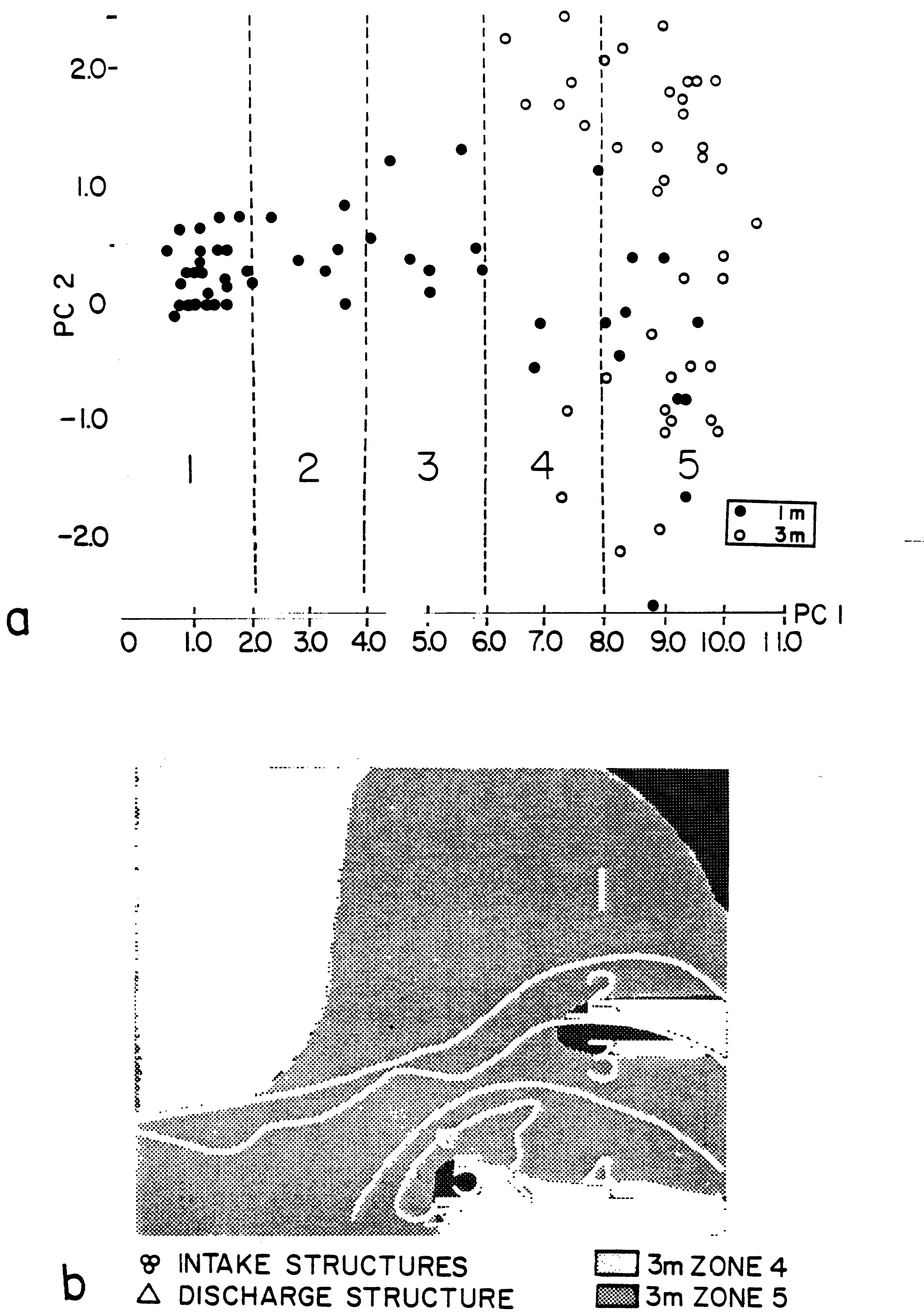

FIG. 56. (a) Ordination of 1-m and 3-m stations (15 June 1977) by principal components 1 and 2 and (b) transect area with regions derived from ordination analysis. The solid lines delineate the regions of the 1-m stratum. Shaded areas delineate the regions of the 3-m stratum.

Groups 4 and 5 consisted both of 1-m and 3-m stations. Group 4 stations at 1 m were located in the vicinity of the power plant. This was an area characterized by higher concentrations of zooplankton than in Groups 1-3 (Table 27). At 3 m, Group 4 stations were located at the northern and southern edges of the transect area in relatively warm water (>15°C) and in the immediate vicinity of the discharge jets. Group 5 stations at 1 m were centered over the discharge jets where concentrations of zooplankton were highest (Table 27). Group 5 also included cooler water 3-m stations located over most of the central and inshore regions of the transect area. Group 5 zooplankton concentrations were greater at 3 m than at 1 m while smaller vertical differences were observed for Group 4.

Detailed information on zooplankton vertical distributions was obtained at three stations. At Stations 1 and 2 zooplankton abundances were low at one meter and more than doubled in the next two meters of water (Fig. 57). These two stations were located outside the body of the plume, and depth distribution patterns probably were representative of the nearshore area.

The third vertical profile station (Station 3) was located east of the intake structures in an area under the direct influence of the plume (Fig. 54). At Station 3, zooplankton occurred in high concentrations at 1-m and in decreasing concentrations with depth (Fig. 57). Although these collections were made late in the day (18:44 to 19:05 EDT), a couple of hours of daylight remained before sunset (21:30 EDT). Thus it is unlikely that zooplankton were beginning their nightward migration toward the surface.

Zooplankton concentrations in the intake forebay ranged from 54,000 to 99,000/m^3 over the course of the study (Fig. 58). This temporal variability was

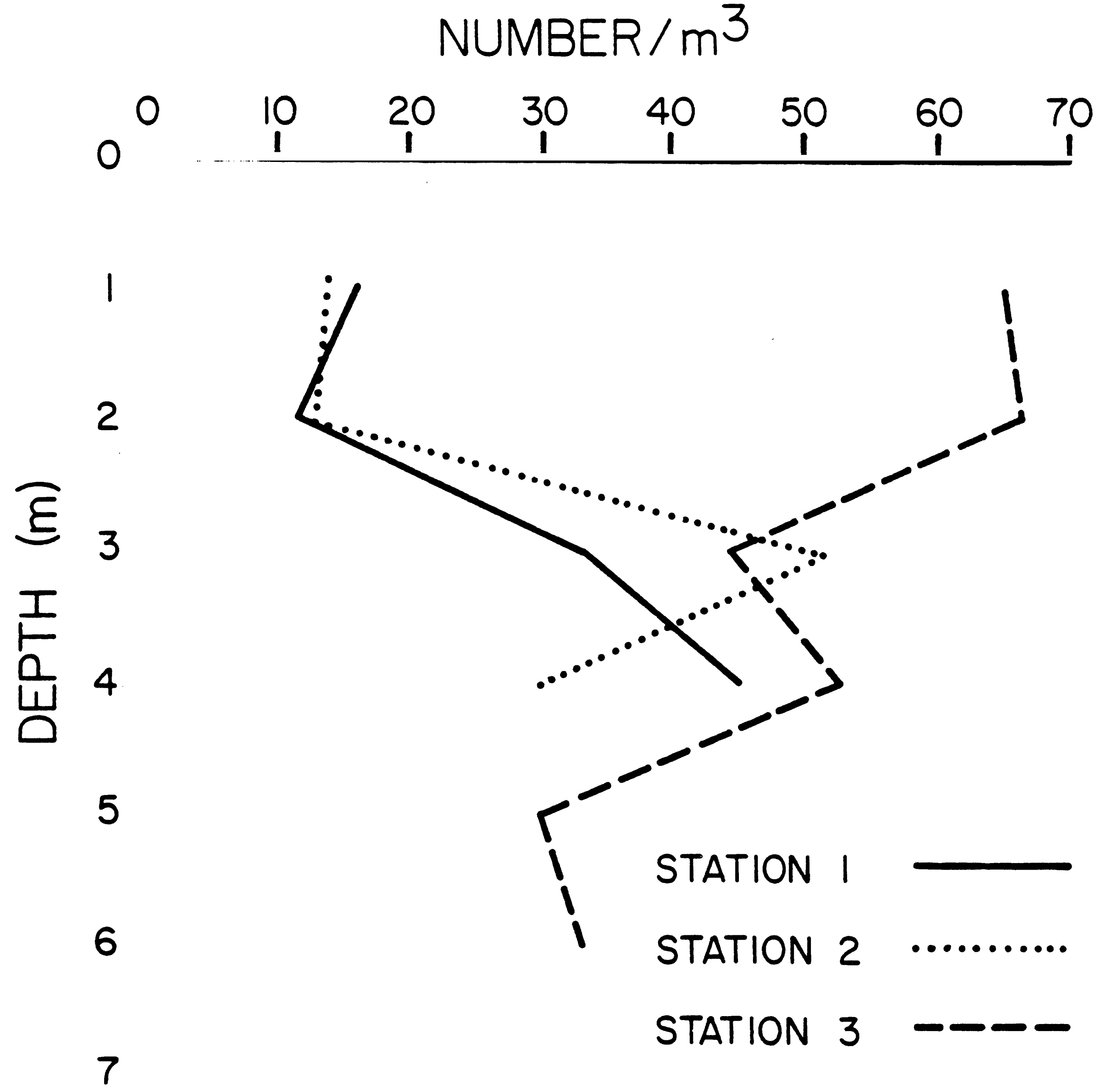

FIG. 57. Depth distribution of total zooplankton at the three stations in the plume transect area. Station locations are shown on Fig. 54.

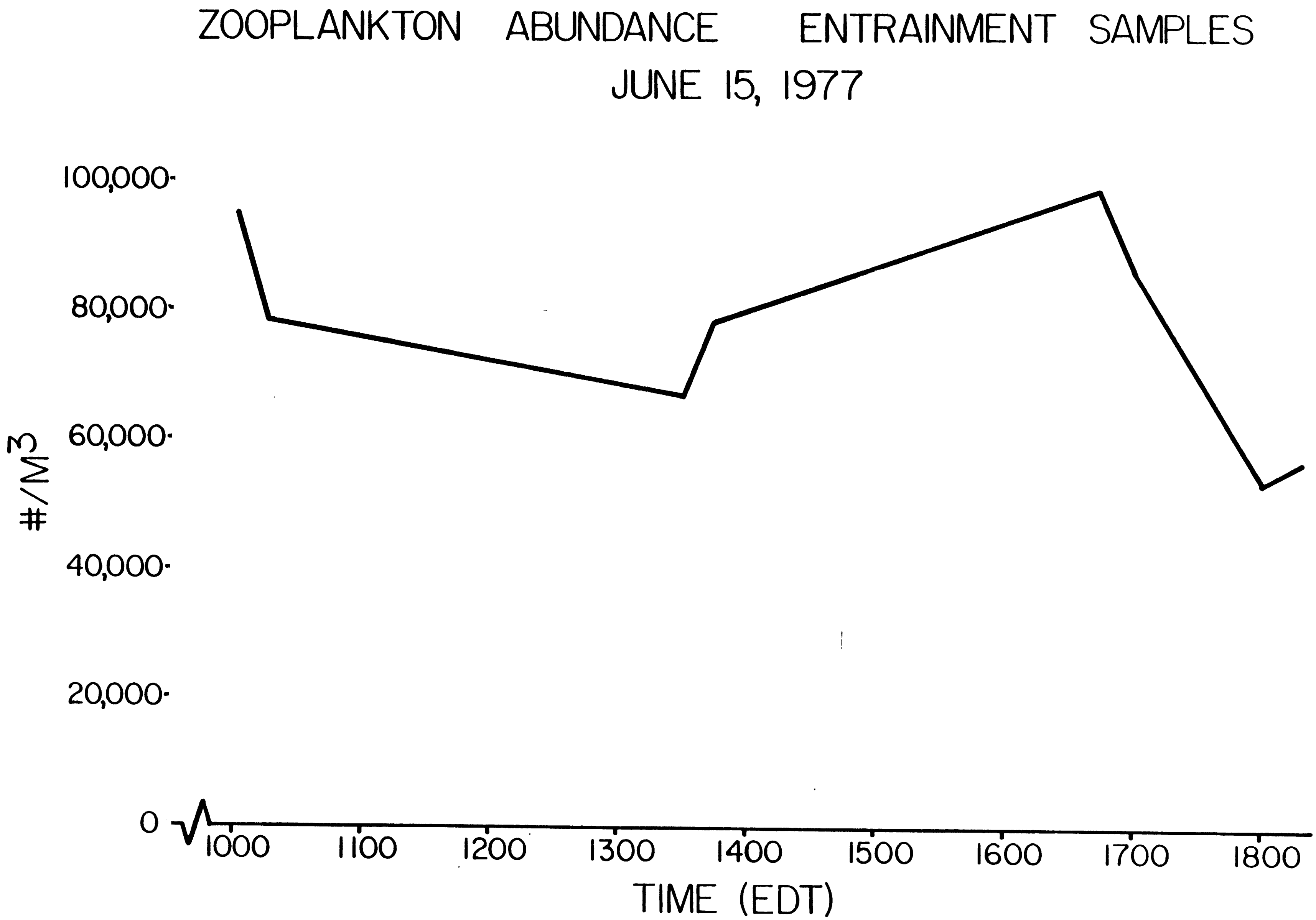

FIG. 58. Total zooplankton concentrations in the intake forebay over the course of the 15 June 1977 plume study.

considerably less than the spatial variability in 3-m zooplankton concentrations where abundances varied from less than 7,000/m^3 to over 144,500/m^3 within a few hundred meters of the intake structures.

DISCUSSION

Although the thermal plume was small in the 15 June study, disruptions in zooplankton distributions were observed over a wide region. As in the 25 September 1976 study, zooplankton occurred in substantially higher concentrations in this area than in the waters 1 km upcurrent and downcurrent of the discharge jets. In both studies, the region of maximum 1-m disruption in zooplankton abundance (Zones 1 and 2 in September, Zone 5 in June) was deflected in a northwest direction and extended a distance of more than 700 m from the discharge jets.

There were differences in the results of the two plume studies. In September, the thermal plume was large and well-defined, extending over most of the transect area. The peripheral plume was large, with the biological boundary of this water (Zones 4 and 6 as described by principal component analysis) roughly corresponding to the thermal boundary between plume and ambient water. There was a moderately high (+0.63) correlation between temperature and PC1. Although the June 1-m thermal plume was poorly defined, the biological characteristics of the plume (Zone 5) were distinct. Peripheral plume water (Zone 4) was detected only from the biological data. The peripheral plume was smaller than in September, apparently compressed by the hydrodynamic events producing the upwelling. In June, temperature was not a good measure of

biological perturbation in the vicinity of the plume. Temperature correlation with PC1 (analysis of 1-m data) was low (+0.21).

Evans et al. (1978) hypothesized that 1-m zooplankton abundances were relatively high in the immediate vicinity of the discharge jets due to vertical displacement. According to this hypothesis, zooplankton avoid the surface layer during daylight hours and occur in higher concentrations at greater depths. However, in the highly turbulent region in the vicinity of the discharge jets, these deeper-living zooplankton are transported to the surface, thus producing a localized 1-m enrichment in zooplankton. As the plume flows away from the discharge jets, it dissipates and becomes less turbulent. Consequently, zooplankton are able to return to their preferred depth. Abundances in the peripheral plume should reflect this, being intermediate to those of plume and ambient waters. Vertical distribution data from Stations 1, 2, and 3 support this hypothesis as zooplankton occurred in their lowest concentrations at 1 m at Stations 1 and 2 and in their highest concentrations at 1 m at Station 3 (Fig. 57). More pronounced differences in zooplankton abundances with depth were observed over the major part of the transect area. In the outer half of this area, zooplankton occurred in concentrations of less than $50/m^3$ at 1 m but in concentrations of over $50,000/m^3$ at 3 m (Table 27). Conversely, low 3-m abundances in the vicinity of the discharge jets may represent dilution of zooplankton-rich deep waters with zooplankton-poor surface waters. The horizontal distribution data also support the hypothesis; highest 1-m zooplankton abundances were observed in the vicinity of the discharge jets (Zone 5) and abundances decreased in the peripheral plume (Zone 4).

The effects of the upwelling on zooplankton distributions is evident from the abundance patterns of taxa such as immature and adult *Cyclops* spp. and *Diaptomus* spp. copepodites, *Daphnia retrocurva*, and *Eubosmina coregoni* -- all occurred in decreasing 1-m concentrations with increasing distances from shore. This is the reverse of the pattern typically observed over the summer during survey cruises when the entire water column is sampled (Section 1). These taxa are metalimnetic, inhabiting the cooler waters in the vicinity of the metalimnion during the day and migrating into warmer epilimnetic waters at night (Wells 1960, Evans unpublished data). The relatively high 1-m concentrations in Zone 3 may be due to upwelling events vertically displacing zooplankton from their preferred depths.

The two plume studies (September 1976, June 1977) have demonstrated that power plant operation disrupts zooplankton distributions in the vicinity of the discharge jets. Greatest disruptions occur in the upper meter of the water column and are localized within 1 km of the discharge jets. As long as zooplankton actively migrate to preferred depths, and the plant discharges large volumes of lake water through subsurface discharge jets, such disruptions will be observed. The plume apparently is strong enough to counteract major hydrological events such as upwellings as the zone of strong disruption in zooplankton population was similar in size in September 1976 and June 1977. It also is evident that temperature alone does not always provide a strong indication of the zone of disruption.

While zooplankton are exposed to physiological stresses during plume entrainment, these stresses probably are not lethal. However, plume-entrained zooplankton may experience enhanced predation by visual-feeding planktivorous

fish. Several authors have noted that fish apparently are attracted to plumes where they exhibit complex swimming behavior characterized by short and rapid turns (Neill and Magnuson 1974, Kelso 1976, Minns et al. 1978). Such behavior occurs even when the plant discharges unheated water and suggests that fish are reacting to currents rather than temperature. While the reason for this behavior has not been investigated, it is possible that fish are feeding. Some support for this hypothesis comes from the observation that in the Cook area, large numbers of sport fishermen travel several miles down the coast to line-fish in the plume. Some of the fish which they catch (yellow perch or Perca flavescens) are facultative planktivores (Scott and Crossman 1973).

Zooplankton avoid predation by visual-feeding fish in two ways. First, during daylight hours, zooplankton inhabit greater depths where they are less likely to be detected by visual feeders (Zaret and Suffern 1976). In the 1-m plume, such zooplankton are highly visible and are available in high densities to predators. Second, zooplankton also avoid predation through escape movements. Such behavior is dependent on the zooplankton's ability to detect suction created by the fish (O'Brien 1979). In the highly turbulent waters of the plume, zooplankton may less effectively detect and avoid predators. Consequently, significant numbers of zooplankton may be killed as an indirect result of plume entrainment -- mortality which is not caused by physiological stresses experienced within the plume but by enhanced predation by planktivorous fish.

CONCLUSIONS

Section 316 of Public Law 92-500 requires that plant operation be such that a "balanced, indigenous population" is maintained in the discharge area (316a) and that cooling water intake structures be designed that "reflect the best technology available for minimizing adverse environmental impact" (316b).

The general conclusion of the 4-year operational (1975 to 1978) study evaluating the impact of the Donald C. Cook Nuclear Power Plant on zooplankton populations in southeastern Lake Michigan is that Unit 1 and Unit 2 operation did not adversely affect the maintenance of a balanced, indigenous population in the discharge area. Furthermore, on most occasions, the cooling water system operated under conditions which minimized immediate zooplankton mortality. Thus, power plant operation appears to have met the general requirements of 316a and 316b.

Mortalities due to plant passage generally were low and probably averaged only 1% or 2% for total zooplankton: *Diaptomus* spp. copepodites, *Daphnia* spp., and *Eubosmina coregoni* were taxa which appeared to be most sensitive to plant passage. Relatively low ΔT's (<12C°) and low discharge water temperatures (<32°C) were of major importance in reducing thermal stresses experienced by plant-entrained zooplankton. However, the mortality studies do suggest that as discharge water temperatures approached or exceeded 32 °C zooplankton mortalities increased. Previous studies reported in Section 3 suggest that zooplankton mortalities at the Donald C. Cook Plant would increase substantially were the plant to operate at Δ-T's of 15 C° to 20 C° or increase discharge water temperatures above 35 °C.

Subsurface discharge jets promoted rapid mixing and cooling of condenser passed water. This rapid cooling minimized thermal stresses experienced by plume-entrained zooplankton. It is unlikely that short-term exposures to temperatures 3 C° or 4 C° above ambient (maximum ambient surface water temperature was 25°C) were lethal or sufficiently long to alter physiological rates to the extent that these rate changes resulted in increased or decreased zooplankton populations in the thermal plume. Exceptions could occur if eddies of warm plume water persisted for longer periods of time. However, extensive plume mapping has provided no evidence of such eddies.

Intense vertical mixing in the vicinity of the discharge jets prevented the water column loss (by sinking) of plant-killed zooplankton. Consequently, these losses could not be detected in samples collected in the vicinity of the discharge jets, immediately preserved, and later examined in the laboratory. While significant settling of dead zooplankton occurred a few hundred meters away from the discharge jets, condenser-passed water and zooplankton were so diluted at these locations that even a 100% loss of zooplankton due to plant passage would not be detected using current sampling methods. Lake currents transport zooplankton several kilometers a day (under average current velocities), constantly replenishing zooplankton standing stocks in the discharge area.

While no strong impact of power plant operation on the zooplankton community in the thermal plume region was observed during the 4-year (1975 to 1978) study, it has not been concluded that damage did not or will not occur. Rather, it is concluded that damage which does occur is below detection limits. The study has been focused on the detection of localized effects of power plant operation on the zooplankton community in the thermal plume region, i.e.,

How well has the plant operated within the requirements of 316a and 316b? Within the spatial constraints of 316a (immediate discharge area), the emphasis clearly has been on the immediate, lethal effects of plant operation. Given the physical nature of the inshore region (rapid water exchange), the reproductive characteristics of zooplankton (generation times generally ranging from days to weeks), and a sampling program designed to measure population size and mortality, the study has been limited to investigating short-term, localized effects. These effects have been shown to be either undetectable (Sections 1 to 4) or of minimal concern (Sections 3 and 5).

The study does not address the possible long-term, lake-wide effects of plant operation on the aquatic community. Considerations of such lake-wide effects, which are outside 316a demonstrations, must include the effects of all the power plants operating on a given water body. This has not been done for the Great Lakes, although earlier studies suggested that the effects of multi-plant usage of Great Lakes waters warranted some concern (Acres 1970, Great Lakes Fishery Laboratory 1970).

One reason why specific power plant studies have not included considerations of long-term, lake-wide effects is that such considerations pose the difficult intractable problem of extrapolating broad ecological effects from a comparatively limited set of observations. There are several examples of limited extrapolative ability. All sublethal effects of plant passage have not been quantified, thus minimizing the ability to predict lake-wide community effects. While phytoplankton productivity is impaired by plant passage (W. Y. B. Chang, The University of Michigan, personal communication), the implications of this impairment to the phytoplankton and zooplankton community are unknown. A large number of fish larvae are killed by plant passage and the

number of fish impinged each year is significant (Kelso and Milburn 1979). However, it is difficult to translate these observations into definitive statements on long-term lake-wide ecological effects of plant operation. Eutrophication, toxic substances, habitat alteration, and commercial and sports fisheries all have their effect on lake community structure. Consequently, power plants are not the only source of perturbation.

Power plant investigations are not uniquely restricted in their predictive ability. Eutrophication studies suffer from the same limitations. For example, phytoplankton have been thoroughly investigated in the laboratory and much is known about their requirements for temperature, light, and nutrients. Similarly, a substantial data base exists characterizing past and present phytoplankton populations in some of the Great Lakes. Nevertheless, there is still uncertainty regarding the precise effectiveness of the phosphorous remedial programs in reversing the temporal trend for increasing phytoplankton standing stocks (Thomann et al. 1979, Chapra 1980). Fisheries management studies also lack precise predictive abilities. Fish physiology has been well-investigated and detailed records of commercial fish catches on the Great Lakes enabled the documentation of the dramatic decline in fish stocks in the 1940s and 1950s (Christie 1974). Despite this wealth of information, the reasons for the declines lack precision. Furthermore, the future for Great Lakes fisheries is indefinite despite numerous continuing studies assessing populations. Despite such uncertainties, the trend for accelerated eutrophication has been reduced and fisheries management has been improved.

Environmental studies require two components - a laboratory component investigating effect pathways under controlled experiments and monitoring studies characterizing populations and investigating change. The literature on

power plant studies suggests that with intelligent plant siting and operation, direct plant effects can be minimized. Furthermore, these studies provide little evidence that continued plant operation will affect long-term changes in the Great Lakes community in the near future. While it is prudent to continue monitoring lake populations, there is little evidence to suggest that long-term, lake-wide effects due to plant operation can be expected or the effect pathways characterized in the immediate future.

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